NOAA Technical Memorandum ERL NSSL-102

OVERVIEW OF REAL-TIME LIGHTNING DETECTION SYSTEMS AND THEIR METEOROLOGICAL USES

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Norman, Oklahoma
October 1993

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Reports in this series are available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151.

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1. INTRODUCTION

The land area covered by *real-time* lightning detection systems has grown significantly during the last decade. These systems detect and locate lightning discharges over large areas with *networks* of antennas that *remotely* detect the electromagnetic radiation from lightning channels. As the technology has matured and been used in more situations and more countries, the benefits have become clear to many users, including weather services. This trend is likely to continue in the coming years. Presently, lightning detection networks are in operation over part or all of three North America countries, part of Australia, five countries in Asia, and nine countries in Europe.

For meteorological applications, uses for lightning data are in several categories:

- Lightning data as a substitute for other types of information on convection, such as provided by radar or satellite sensors, when data from these systems are temporarily missing or not available at all.
- The real-time feature of lightning detection networks provides second-by-second information about thunderstorms that often is not available from these other sensors.
- Lightning activity is a potentially valuable covariate with radar and other data to identify trends and coverage of the convective weather situation in a way that is not possible with any single sensor alone.
- Flashes identify the general nature of the threat from forest and range fires.
- Lightning is one of the most significant meteorological causes of deaths and injuries, and a direct monitoring of this threat over large areas could help to reduce the number of lightning casualties through direct warnings and short-term forecasts.

The methods of lightning detection in use today are very different than only a decade ago. Only commercially-available systems will be described in this report. The most common system in real-time use is the direction-finder (DF) antenna network. Another common system in use by weather services is the time-of-arrival (TOA) antenna network. Another less common approach is the radiometric interferometry lightning warning system (SAFIR). These systems constitute a new generation of instruments that have been developed within the last 15 years. Three broad categories of scientific and technological advances, originating primarily outside the meteorological community, have made such real-time network lightning detection a reality:

- Major advances in communications capabilities
- Enormous improvements in electronic design
- Improved understanding of lightning discharges and associated electromagnetic fields.

This report reviews the operation principles of this new generation of real-time lightning detection networks, and outlines some of the meteorological applications that have been developed. The discussion is restricted to detection of lightning by systems that cover a large enough region to be of interest to meteorological services. Not included in this report are single sensor systems that detect lightning in a limited area around the sensor, and provide only a general indication of its location. Also not included are other systems that are either experimental or not commercially available.

2. METHODS FOR LIGHTNING DETECTION BY REAL-TIME NETWORKS

A. THE LIGHTNING DISCHARGE - BASIC PROCESSES AND TERMINOLOGY

Lightning discharges can be divided into two types:

- Cloud-to-ground (CG) discharges, which have at least one channel connecting the cloud to the ground
- Cloud discharges that have no channel to ground. These cloud discharges can, in turn, be classified as in-cloud, cloud-to-air, and cloud-to-cloud.

Most of the practical meteorological interest in lightning detection focuses on cloud-to-ground (CG) lightning discharges. In addition, the two major detection systems in general use today are designed for detecting CG lightning. However, cloud lightning may also be important for meteorological applications. Recent research indicates that detection of cloud lightning could be a useful tool for nowcasting (Juvanon du Vachat and Cheze, 1993) and for assessing severe weather characteristics of convective storms such as microbursts and tornadoes (Goodman et al., 1988c, 1989; Buechler et al., 1988, 1989; Laroche et al., 1991a,b; MacGorman et al., 1989).

In order to better understand the prevalent CG detection technology, and to define the terminology to be used in the rest of this report, we present a short description of CG lightning discharge processes. Excellent reviews and explanations of this subject are by Uman (1969, 1987); these two references are given at the end of this section. A good summary by Fisher (1992) is in the list of lightning network publications in section 5 of this report.

A CG lightning discharge is typically initiated inside the thundercloud. It is first apparent when a faint negatively charged channel, the *stepped leader*, emerges from the base of the cloud. Under the influence of the electric field established between the cloud and the ground, the leader propagates towards the ground in a series of luminous steps of about 1 microsecond in duration and 50 to 100 meters in length, with a pause between steps of about 50 microseconds. The stepped leader reaches the ground in tens of milliseconds depending on the tortuosity of its path. When the stepped leader channel approaches the ground, it has about 5 Coulombs of negative charge on it and carries a very strong electric potential with respect to ground of about -10^8 volts.

The strong electric field between the leader and the ground causes upward-moving discharges, or *streamers*, from objects on the ground. When one of these streamers contacts the tip of the leader, 50 to 100 meters above the surface, the following occurs:

- The leader channel is connected to the potential of the ground
- Charge starts flowing to the ground
- Current wave propagates as a bright pulse up the channel.

This discharge process is called a *return stroke* and takes less than 100 microseconds. The charge deposited on the leader flows down the channel behind the wave front producing a current at the ground that has an average peak value of about 30 kiloAmperes. It takes about 1 microsecond for the current to reach its peak value, and about 50 microseconds to decay to half that value.

As the leader charge flows down the channel to the ground, electric and magnetic field changes are produced that propagate outwards from all segments of the channel involved in the current flow. These field changes have rapid variations that follow the variations of the current flowing down the channel of the stepped leader. The field changes have electrostatic, inductive, and radiative components, and each of these components has fluctuations of different frequencies that have different attenuation characteristics as the fields propagate from the lightning channel. Therefore, the shapes of the field changes are strong functions of radial distance from the channel. The detailed structure of the first several microseconds of the electric and magnetic field changes produced by the return stroke is of fundamental importance in the lightning detection systems described below.

After the current has ceased to flow down the stepped leader channel, there is a pause of about 20 to 150 milliseconds. After that, another leader can propagate down the already established but faint lightning channel. This leader is not stepped, but rather continuous and is called a *dart leader*. On the other hand, no dart leader might occur and the flash may end. A dart leader is produced when additional charge is made available to the top of the decaying channel in less than about 100 milliseconds by breakdown mechanisms known as K- and J-processes. The dart leader deposits about one Coulomb of charge along the channel and carries cloud potential to the vicinity of the ground. Again a return stroke is produced. The peak amplitude of the current flowing in subsequent return strokes is usually, but not always, smaller than that of the first return stroke. As a consequence, the induced field changes are also usually smaller in amplitude and have shorter durations than those of the first return stroke. Dart leaders and return strokes subsequent to the first are normally not branched. The combination of leader and return stroke is known as a *stroke*. All strokes that use essentially the same channel to ground constitute a single cloud-to-ground *flash*. A flash might be made up of one to a few tens of strokes.

Lightning discharges to ground can also be initiated by downward-moving leaders that are positively charged. The resulting return stroke effectively lowers positive charge from the cloud to the ground. The combination of leader and return stroke is then called a positive stroke. Usually, there are no subsequent leaders down the existing channel, so that only one stroke makes up a *positive flash*. Generally, positive flashes constitute only a few percent of all CG flashes. The peak current of their return strokes, however, can be larger than the peak current of negative return strokes and, thus, can cause greater damage than negative flashes. A large percent of forest fires and damage to power lines is probably caused by positive flashes.

There is an extremely small percentage of flashes that are initiated from the tops of buildings and towers, as well as those triggered by rockets attached to ground by wire. Their leaders move up to the cloud, and their channels branch upwards.

Uman, M.A., 1969: *Lightning*. Dover Publications, Inc., New York, 298 pp.

Uman, M.A., 1987: *The lightning discharge*. International Geophysics Series, 39, Academic Press, Inc., Orlando, Florida, 377 pp.

B. MAGNETIC DIRECTION FINDER (DF) NETWORKS

Direction-finder (DF) lightning location systems are based on classical radio direction-finding technology developed several decades ago. Two or more crossed-loop antennas located at different places are used to detect the magnetic field emitted by the return stroke current. Each antenna consists of two vertical loops perpendicular to each other and oriented north-south and east-west, respectively. The signal induced in each loop depends on the inclination of the lightning channel, the current flowing in the channel, and the angle between the plane of the loop and the bearing or azimuth to the lightning channel. By taking the ratio of the signals induced in each of the two loops, the ratio depends on only the inclination of the channel and its bearing. If the channel is fairly vertical, the bearing to the lightning flash can be determined for each crossed-loop antenna. The actual location can then be determined by triangulating signals from different antennas.

The major technological improvement to classical radio direction-finding by Lightning Location and Protection, Inc. (LLP) in the 1970s consisted of a patented time-gated, wide band, wave form discrimination algorithm that is used to process all incoming signals at each DF. This algorithm identifies the initial radiation peak of the magnetic field. This peak is associated with the beginning of the return-stroke current roughly 100 meters from ground. At that point the channel is predominantly vertical and, thus, its azimuth can be obtained quite accurately. In addition, concentrating on the lower 100 meters or so of the channel has the advantage of obtaining the location of the channel at the point of ground attachment, so that location uncertainties due to the tortuosity and branching of the channel can be avoided.

The LLP system also discriminates against signals from noise and cloud flashes by examining certain features of the shape of the incoming signal wave form. If those features satisfy certain criteria, previously established from the statistical analysis of a number of waveforms from known cloud-to-ground flashes, the signal is considered to have originated by a lightning stroke to ground. Signals not passing the pre-established criteria are rejected. Once a CG return stroke is detected, the DF counts the number of subsequent return strokes identified as being part of the same flash, and produces one record giving the azimuth, peak signal strength, total number of return strokes, and the polarity of the flash (whether the discharge brought negative or positive charge to the ground). The polarity of the CG flash is determined by a flat plate electric field antenna. The flash record is then transmitted to a central processing site.

At the central site, the records from all the DFs of the network are received. A *Position Analyzer* (PA) takes all the DF records arriving within a preset time window (typically 20 milliseconds or less), assumes that the DFs detected the same flash, and calculates the location of the lightning strike to ground. Basically, only 2 DFs are needed to locate a flash. Figure 1 illustrates this situation. Solid lines represent the measured bearings to the flash, and dashed lines outline the angular random error in azimuth measurements. This error is typically less than 1° for the earlier DF models and less than 0.5° for the newer ones. The dot indicates the computed flash location while the shaded region indicates the area where the flash probably occurred. A complication arises when only 2 DFs detect the flash and the flash lies close to the baseline (Figure 2). In that case, the PA assumes that the flash occurred along the baseline and uses the ratio of the signal strengths to position the flash. When 3 or more DFs detect the same flash, there is redundant information for the triangulation calculation, and the flash location can then be obtained by a method that minimizes the chi square of the differences between the measured azimuth and the computed one. Figure 3 portrays this situation. The lines represent the measured azimuths to the flash. In this situation, 3 possible locations are defined by the 3 different intersections of the bearing vectors (open circles). The PA then computes the position (solid dot) that would minimize the square differences between observed (solid lines) and computed azimuths (dashed lines). For clarity, the region enclosed by the 3 intersections has been drawn much larger than it is in real situations relative to the DF spacing.

Early lightning research leading directly to DF technology is described by Herrman et al.

(1976); Krider et al. (1976, 1980); Lin et al. (1979); and Uman et al. (1980). Two good summaries of DF detection technology are by MacGorman et al. (1991) and Fisher (1992).

The DF lightning detection equipment is manufactured by Lightning Location and Protection, Incorporated (LLP) of Tucson, Arizona. GeoMet Data Services (GDS) is collocated with LLP and operates the national lightning detection network of direction-finder antennas for the continental United States, and sells the data to a variety of users. The growth of the U.S. national network using DF technology can be followed with Binford et al. (1983); Maier et al. (1983); Orville et al. (1983a,b, 1990); Orville and Songster (1987); Nadis (1989); Orville (1991a, 1993).

Studies with DF technology outside its origin in the U.S. have been in Canada (Jackson, 1982; Raynor, 1982; Nimchuk, 1985; Janischewskyj and Chisholm, 1992); France (Helloco and Krider, 1989; Tourte et al., 1988, 1989; Le Boulch, 1989; Le Boulch and Plantier, 1990; Juvanon du Vachat and Cheze, 1993); and in Sweden (Murty and Lundquist, 1983; Israelsson et al., 1985; Melin, 1990, 1991; Namasivayam and Lundquist, 1991).

Principal sources of error for DF systems are topographic features and man-made structures that intercept and reradiate, in a different direction, the electric and magnetic field signals produced by lightning discharges. The errors that are introduced are specific to each antenna site, and called *site errors*. These errors are a function of azimuth to flash location, and depend on distributions of terrain features and man-made structures around antenna sites. They tend to be fairly constant with time and, when determined for a DF, measured azimuths can be corrected in real time.

Several schemes have been devised for correction of site errors (Mach, 1984; Hiscox et al., 1984; Guillo, 1985; Mach et al., 1986; Orville, Jr., 1987; Schütte et al., 1987a,b; Kawamura et al., 1988; Passi and López, 1989; Chao and Qiming, 1991; López and Passi, 1991; Anderson, 1993; Tyahla and López, 1994). All methods depend on statistical analysis of previously recorded data. Usually, data from one thunderstorm season are enough. Once corrections are applied, residual azimuth measuring errors are 0.5° or less.

Flash location accuracy by a network of DFs depends mainly on distances between DFs, network configuration, and flash position within the network. Average location accuracy of the National Lightning Detection Network (NLDN) as presently configured by GDS is estimated between 2 and 4 km, depending on flash location. DF separation for this network is on the order of 250 to 300 km. For smaller networks with DF separations of tens of km, location accuracy can reach 0.4 to 0.5 km (Maier, 1991a, b).

Network detection efficiency is also a function of network configuration, antenna separation, and location of flashes with respect to the network. It also depends on DF gain. An important factor determining whether a flash is detected or not is the attenuation of flash signal with distance. If the magnetic field strength of a flash is not large enough to reach at least two DFs with a value above DF threshold, flash location cannot be determined. Another factor apparently limiting detection of all CG flashes is that wave form criteria used to accept a flash as cloud-to-ground may not be adequate for CG flashes in all geographical regions and all weather situations (Ishii and Hojo, 1988, 1989). A similar situation arises when the flash's signal strength is too small and the wave form fails to satisfy the acceptance criteria (Maier, 1992). In some cases, LLP has modified wave form discrimination parameters. Present estimates (MacGorman and Rust, 1988a,b,c, 1989; Cummins et al., 1992; Maier, 1992) put the detection efficiency of DF networks at 60 to 90% depending on network configuration, DF separation, and flash location.

Over the last few years, LLP has developed a method for lightning location that combines direction finding and time-of-arrival information (Cummins et al., 1993). This method, called *Improved Performance from Combined Technology* (IMPACT) by LLP, estimates both the location and time of occurrence of the return stroke. Each sensor provides information on azimuth and the time it took the signal to propagate from its origin to the station (absolute arrival time minus the estimated time of occurrence). The azimuth establishes a vector from the sensor to the stroke, while the propagation time establishes distance (range), thus defining a circular locus of possible locations around the sensor. Ideally, the location and time of occurrence of the discharge are obtained by selecting the position and time that cause all circles and vectors to intersect. In practice, location and time are determined by iteratively adjusting initial estimates of these parameters so that differences between observed and calculated azimuths and propagation times are minimized. When only two stations detect a flash, there is redundant information for an optimized estimate of location. In that case there are four measured parameters (two azimuths and two arrival times), while only three parameters are estimated (latitude, longitude, and time). Location accuracy has been estimated as 500 meters or better in areas surrounded by sensors using the IMPACT location algorithm.

Although LLP systems detect and analyze individual return strokes from each flash, they group all strokes that belong to the same flash and provide only one data record per flash. This record contains time, location, and peak signal amplitude of only the first return stroke, but provides multiplicity or number of strokes that made up the flash. If the user wants the total number of strokes over an area, the multiplicity of all flashes is added over the region of interest. New systems with IMPACT technology will provide information for each stroke.

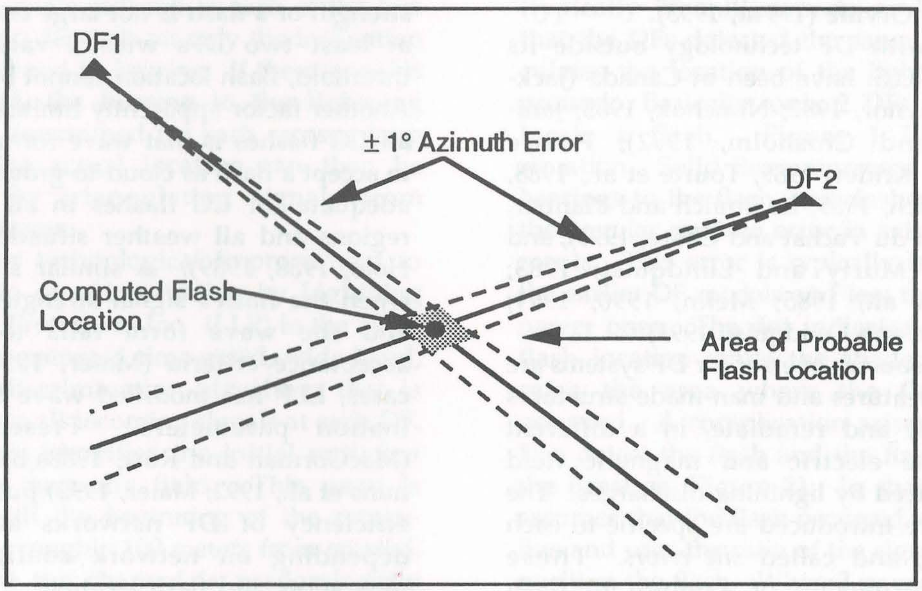

FIGURE 1. Determination of flash location when only 2 DFs detect it. Solid lines represent measured bearings to the flash; dashed lines outline the angular random error in azimuth measurements. Dot indicates computed flash location; shaded region indicates area where flash probably occurred.

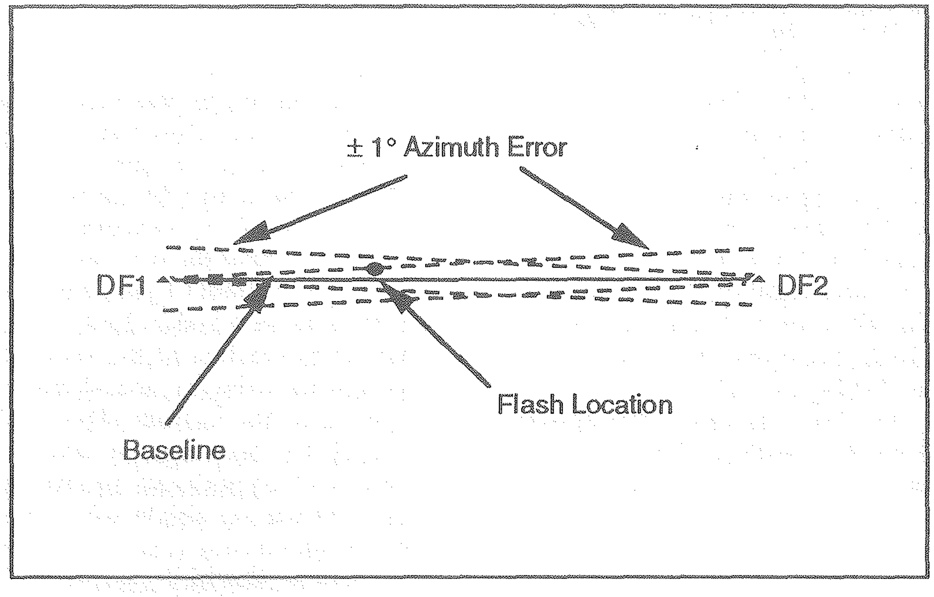

Figure 2. Determination of flash location when only 2 DFs detect flash close to baseline. The Position Analyzer assumes that flash occurred along the baseline and uses the ratio of signal strengths to position the flash.

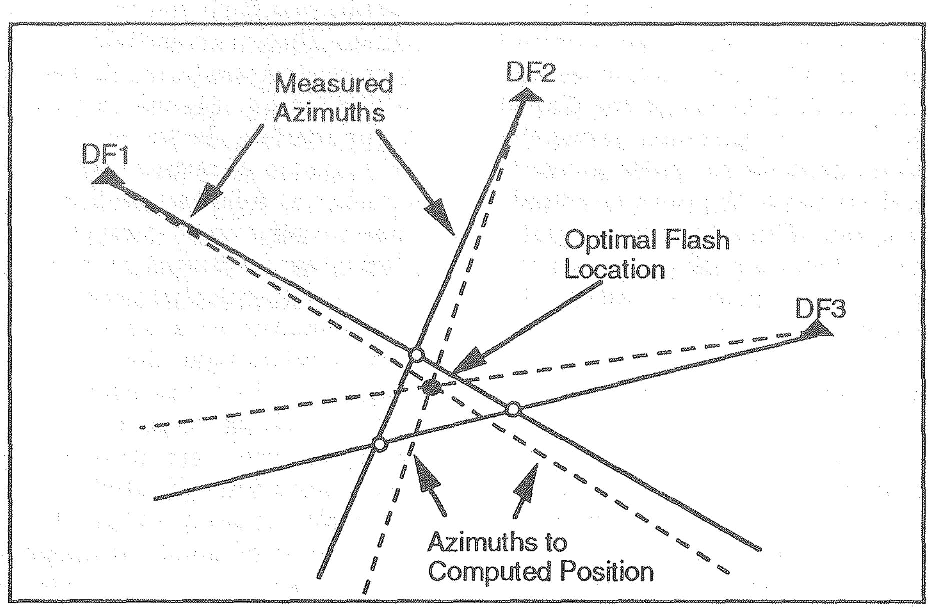

Figure 3. Determination of flash location when 3 DFs detect it. Solid lines represent measured azimuths to flash. Open circles indicate the 3 possible locations defined by 3 different intersections of azimuth vectors. The Position Analyzer computes the position (solid dot) that would minimize the square differences between observed (solid lines) and computed azimuths (dashed lines).

C. TIME-OF-ARRIVAL (TOA) NETWORKS

Time-of-arrival (TOA) lightning detection systems are based on determining differences in arrival times at various stations of the electric pulse emitted by a lightning discharge. This methodology has been used in different countries for the detection of lightning since the early 1970s. A commercial TOA system called Lightning Position and Tracking System (LPATS) was first developed and manufactured early in the 1980s by Atlantic Scientific Corporation, that later became Atmospheric Research Systems, Inc. (ARSI). The system uses an array of four or more simple whip antennas roughly configured in a square and separated by 200 to 400 km. Each station detects the electric pulse emitted by a return stroke and assigns to it the time of arrival of its peak amplitude. As discussed before, the peak amplitude corresponds to the initiation of the return stroke current when the leader channel is approximately 100 meters from the ground.

The antenna stations must be synchronized to a dependable absolute time standard such as a television station, LORAN-C, or the Global Positioning System. Each station sends the information about each electric pulse it detects and the time of arrival of the peak amplitude to a *central analyzer*. This analyzer computes the difference in the time of arrival of the lightning signal between pairs of stations. For a given time-of-arrival difference between a pair of stations, the stroke that emitted the signal could be located anywhere along one of the branches of a hyperbola that passes between the two stations and has as foci the two station locations, as illustrated in Figure 4. Although the branch of the hyperbola along which the stroke is located can be defined by the sign of the time-of-arrival difference, the specific location of the stroke can not be determined. When three stations detect a stroke, however, two non-redundant hyperbola branches are defined. As shown in Figure 5, the intersection of these can define the location of the stroke (open circle). In some situations, however, the two hyperbola branches can intersect at two points, one close to the network and another away from it. This situation is illustrated in Figure 6, where the two open circles represent the two intersections, one corresponding to the stroke position and the other one not. Two hyperbola branches will intersect in two points in the case of stroke signals originating in the region outside of the area enclosed by the baselines, between the lines extending the baselines outwards. In this case a minimum of four stations (giving three different non-redundant hyperbolas) must report the arrival of the signal from the same stroke in order to unambiguously locate the source of the signal. The stroke location is found by solving for the intersection of spherical hyperbolic equations modified to account for the oblate spheroidal shape of the earth.

Unlike the LLP system, LPATS does not employ waveform discrimination to determine if the electric pulse received at an antenna site is from electric noise, a cloud, or a CG stroke. Nor does LPATS discriminate between the first stroke of a flash and strokes subsequent to the first. Thus, each individual station reports to the central analyzer all electric field pulses detected. Signal attenuation due to propagation, however, contributes to the elimination of many, although not all, non-CG strokes as follows: non-lightning noise signals are usually weak compared to signals from lightning discharges. Likewise, cloud strokes produce signals that generally, but not always, have smaller peak amplitudes. Cloud pulses also tend to have their largest amplitudes at higher radio frequencies than those of CG strokes. Thus, noise and cloud stroke signals will be much more attenuated by propagation than those from CG strokes. Since sensors are typically located 200 to 400 km apart, the probability of simultaneous detection of a non-CG stroke by the 3 or 4 stations needed for location would be small, and many non-CG signals would tend to be discarded in that way.

ARSI now examines the width of the detected pulses to distinguish between cloud and CG strokes. Generally, cloud lightning pulses are narrower than those from CG strokes. ARSI uses a 10-microsecond pulse width criterion to determine if a pulse is from a cloud or a CG stroke. If at least one of the stations detecting a stroke reports a pulse shorter than that value, the source is not regarded as a CG stroke. ARSI has estimated that using this technique, only 2% of the strokes reported by LPATS are from cloud lightning. However, Casper (1991) estimated that 30% of the total detected population is cloud lightning. Ishii et al. (1992a,b) used an LPATS network (with baselines of 130 to 180 km) that used the 10-microsecond criterion to eliminate cloud strokes. Their results indicate that 30% of all detected flashes in the summer were positive, while typically less than a few percent of all CG flashes are positive in Japan during the summer. They attributed the additional positives to cloud bipolar pulses having a duration of 20 to 150 microseconds. Narrow bipolar pulses from other kinds of cloud discharges, however, were effectively filtered out by the 10-microsecond criterion.

The time-of-arrival lightning detection equipment is manufactured by Atmospheric Research Systems, Inc. of Palm Bay, Florida. The growth of the national lightning network using TOA technology in the United States can be followed with Bent et al. (1983); Lyons and Bent (1983); Bent and Lyons (1984); Lyons et al. (1985a,b,c, 1989d); Lyons and Pielke (1988); Casper (1991); Casper and Bent (1992); Cook and Casper (1992); and Ishii et al. (1992a,b).

Published studies with TOA technology outside its origin in the U.S. have been in Australia (Ryan and Gunn, 1993); Japan (Ishii et al. (1992a,b); and the Netherlands (Janssen, 1988, 1989).

A major source of error for TOA systems is the changes in waveform of the signal as it propagates from the stroke location to the different antennas. LPATS depends on an accurate timing of the first waveform peak after the signal crosses the threshold of the sensors. Propagation of the signal effectively moves the peaks in time relative to the threshold crossing. Thus, there is an additional delay in detecting the arrival of the peak beyond what it would take the peak to reach the station had it not shifted. The amount of distortion decreases with distance from the lightning stroke. If possible, LPATS does not use the time samples from the closest receivers in the location solution process in order to minimize this effect. The degree of distortion, and the effect on location accuracy, also depends on the conductivity of the ground. Thus, Janssen (1989) has reported an average location accuracy of 300 meters for an LPATS system in Holland in a low lying, flat terrain area with generally high ground conductivity. On the other hand, Montandon (1992) has reported location accuracies of several hundred meters to 4.2 km for a system that is located in Switzerland in a mountainous terrain area with considerably lower ground conductivity. For the same system, Casper (1991) has reported location errors of up to 2 km, due primarily to the enhanced propagation effects on the waveforms of the signals.

An important factor determining network efficiency is the attenuation of stroke signal with distance. If the electric field strength of a stroke is not large enough, or if the stroke is too far to reach at least 4 antennas with an amplitude above threshold, an unambiguous location cannot be determined and the stroke is lost to the system. ARSI tries to set up their networks with fairly large antenna baselines (200 to 400 km) in order to filter out cloud pulses and to minimize the effect of widely varying waveforms. That, and the requirement of having at least four antennas detecting the pulse, reduces the detection efficiency of the system. Another situation reducing detection efficiency occurs when a thunderstorm is located very close to an antenna. In that case, too many radio pulses from cloud lightning could be detected, overloading the station's processing capability (MacGorman et al., 1991). In that situation, LPATS turns off the station, thereby reducing the number of stations available for the unambiguous detection of lightning events farther away. On the other hand, a factor tending to artificially increase detection efficiency is the inclusion of cloud strokes as part of the CG stroke population as noted above. Janssen (1989) reported a detection efficiency of 92% within the primary coverage area of a 125-km baseline network in Holland. Fisher (1992), however, is of the opinion that some of the procedures employed by Janssen appear to bias the predicted detection efficiency in the optimistic direction. The early evaluation of MacGorman and Rust (1988a,b,c, 1989) suggested a detection efficiency of between 40 to 55% of the CG flashes. In addition, ARSI has calculated a theoretical value of between 90 and 99%.

It should be emphasized that LPATS does not discriminate between the first stroke of a flash and strokes using the same channel subsequent to the first. The position information that is normally displayed by LPATS systems is only provided for individual strokes, whether they belong to the same flash or not. If the user wants to be able to combine all of the strokes corresponding to the same flash, the time and distance clustering criteria need to be specified for the subsequent strokes. For example, a rule to construct a flash can be established that a subsequent stroke is one that occurs within 500 milliseconds of the first or previous subsequent stroke, and is located within 10 km of the first stroke of the same flash (Casper and Bent, 1992).

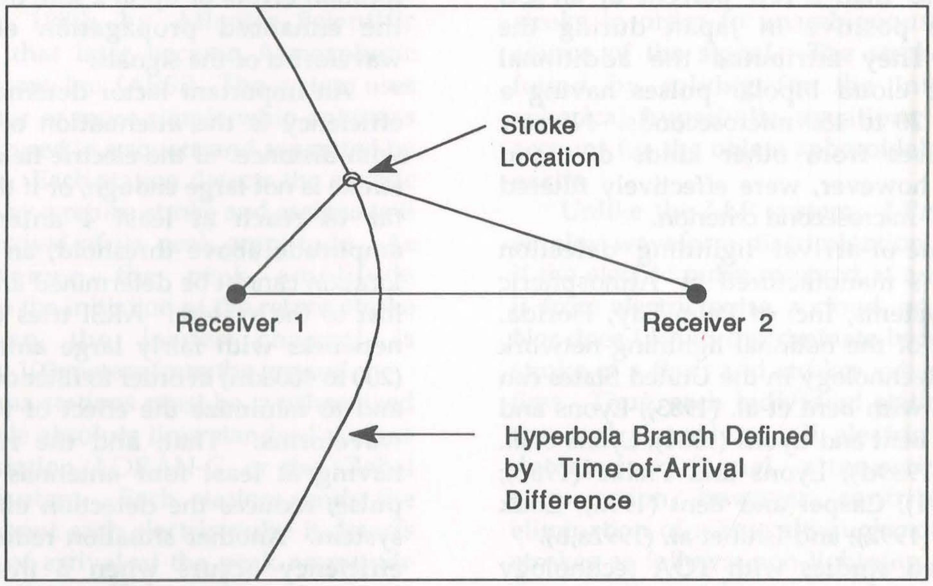

FIGURE 4. Detection of a stroke by two TOA receivers. For a given time-of-arrival difference, the stroke that emitted the signal could be located anywhere along one of the branches of a hyperbola that passes between the two receivers and has as foci the two receiver locations.

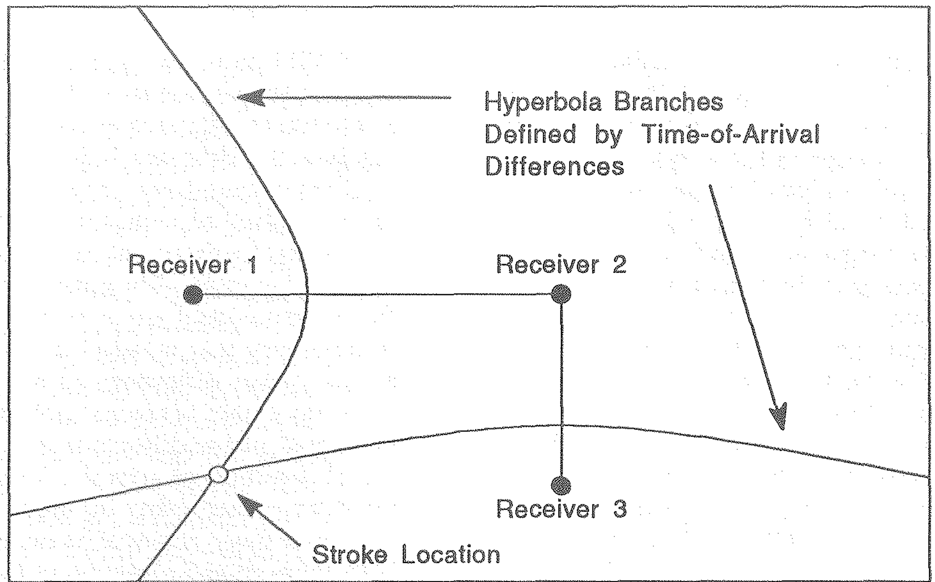

Figure 5. Detection of a stroke by 3 TOA receivers. Two non-redundant hyperbola branches are defined whose intersection can define the location of the stroke (open circle).

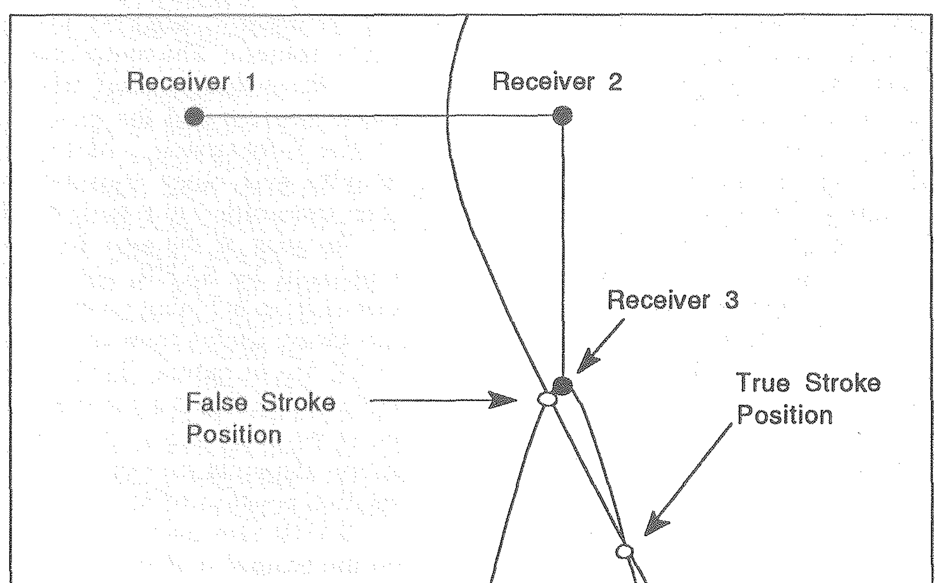

Figure 6. Detection of a stroke by 3 TOA receivers. Two hyperbola branches are defined that intersect at two points (open circles); one corresponds to the stroke position and the other does not.

D. TOTAL LIGHTNING DETECTION SYSTEMS

The French Office National d'Etudes et de Recherches Aérospatiales (ONERA) has developed a system that detects and locates lightning discharges of all types in three dimensions. The localization of electrical activity is achieved by Very High Frequency (VHF) electromagnetic interferometry. The system detects and locates sources of VHF radiation that are present in all types of lightning discharges. The firm Dimensions, of St. Aubin, France, manufactures and markets the equipment Systeme d'Alerte Foudre par Interferometrie Radioelectrique (SAFIR). Origins of the French lightning detection system using SAFIR technology can be traced with Boulay et al. (1989); Richard (1990, 1991a, 1992); Richard et al. (1988, 1989, 1990); and Kawasaki et al. (1992).

Lightning discharges emit electromagnetic radiation over a large frequency spectrum. The most intense radiation comes from the return stokes of CG discharges at a low frequency mostly below 1 megaHertz. Lightning discharges, however, emit much more profusely within the VHF band (roughly 30 to 300 megaHertz). In this and the Ultra High Frequency (UHF) band, the signals consist of isolated and short bursts of pulses with durations ranging from a few hundred microseconds to a few milliseconds. The typical separation between pulses is about 50 to 100 microseconds. These radiation pulses come from all portions of the lightning channels, both during their formation as well as during the current propagation along them. They are principally due to fast transitions between low and high conductivity phases of the lightning channel plasma. Both cloud and CG strokes emit these pulses during most stages of development: preliminary breakdown, stepped leader, dart leader, recoil streamers and return stroke.

SAFIR samples the highly impulsive electromagnetic signals in a VHF band with a time resolution of 100 microseconds. Thus, the system resolves the different lightning events as successions of impulsive single point sources. The total number of samples per lightning flash ranges from a thousand to ten thousand for the most active ones. The sources are localized in three-dimensional space by the principle of interferometry that is based on the measurement of the phase difference of an incident plane wave on a pair of electric field whip antennas. Measured phase difference is a function of the signal direction of arrival. Antennas are separated from each other by about one meter. A cluster of three antennas is necessary to obtain both azimuth and elevation of the point source.

A basic SAFIR system consists of three detection stations and a central processing station. The distance between stations can be from 20 to 100 km. Each detection station contains three electric field whip antennas that perform the interferometric angular localization of the signal sources. The central station performs the final three-dimensional triangulation of the signal sources and the main real-time display of the information. Maps of the electrical activity and other warning information are then transmitted to remote display terminals.

Because of the very high frequency band employed by SAFIR, signals are usually received from lightning no more than roughly 200 km away; useful coverage is basically an area of 150 km in radius. Typical spatial resolution is 500 m within the network and 5 km at the outer edges of the service area. Actual resolution depends on system configuration and relative position of lightning.

SAFIR also uses an electrostatic field mill on the ground to detect the early electrification of clouds that are developing at short range.

E. CONCLUDING COMMENTS

The SAFIR system can provide detailed three-dimensional information on cloud and CG lightning channels for a relatively small area around a particular location or installation.

DF systems can provide highly accurate CG *flash* locations with a high detection efficiency over small areas with short-baseline networks of 4 to 5 DFs. These systems can also cover medium to large areas with networks of DFs that are separated from each other by 100 to 300 km. Medium to high detection efficiency and accuracy can be achieved, depending on network configuration and the position of the storms relative to the network. With the new IMPACT technology, accuracies can be as high as 500 meters within networks covered by IMPACT sensors. DF systems need to be calibrated for site biases and, in some cases, for waveform discrimination criteria. This requires collecting and statistically analyzing data for a period of time before the calibrations are incorporated operationally. Usually one thunderstorm season or a representative portion of one season suffices.

TOA systems can cover medium to large areas with networks of sensors located 200 to 400 km apart. These systems provide localizations of *strokes* with medium to high accuracies and detection efficiencies depending on network configuration, position of storms relative to the network, and the nature of the topography over which the lightning signals propagate. Within short-baseline networks over flat uniform terrain, detection efficiency and accuracy can be very high. TOA systems do not discriminate between cloud and CG stroke waveforms, and although there are features to filter out cloud strokes, a considerable portion can still be accepted and reported. Presently, there is no way to distinguish between the CG and cloud strokes reported by the TOA systems. Most of the cloud strokes that are not filtered out are indistinguishable from positive CG flashes. Presently, there is no procedure to correct for the location biases due to differential propagation effects on waveforms.

Comparative evaluations of results from the DF and TOA lightning network methods were made by MacGorman and Rust (1988a,b,c, 1989). It is important to note that such comparisons apply to the networks as they were configured at the time of the comparisons.

Lightning detection satellites are planned to be deployed over the next few years. A first-phase model is scheduled to be launched during 1994, and the fully-functional model a few years later as part of NASA's Tropical Rainfall Measuring Mission. The sensor was developed by NASA and is an optical array of charge coupled devices with electronics capable of detecting light fluctuations from lightning flashes at any time, including daytime. From work with prototypes and high flying aircraft, NASA estimates that the system will detect 90% of all lightning that occurs in daylight. Flash data will be collected at each location in low latitudes twice a day in bins that are smaller than 10 by 10 km. It will collect total lightning, and not distinguish between ground strikes and cloud lightning. The flash information collected by this satellite could prove to be useful to meteorological services for real-time monitoring of convection over tropical and subtropical oceans and land masses.

3. OPERATIONAL AND RESEARCH USES OF LIGHTNING NETWORK DATA

A. NON-METEOROLOGICAL USES IN OPERATIONS

As real-time lightning detection networks were established in the U.S. and many other countries, the first two operational users usually were forest fire detection agencies and utility companies. These operational uses of lightning network data have the ground strike as the most important parameter.

• Forest fire detection

The application of lightning network data to forest fire detection and monitoring for the western U.S. and Alaska is described by Krider et al. (1980). The Bureau of Land Management (BLM) installed a real-time lightning network for early detection of forest and rangeland fires, and used network data for significant cost savings. A main benefit is eliminating initial searches for lightning with reconnaissance aircraft or ground crews. Also, the lightning network aids forecasting and nowcasting by identifying lightning-producing storms at an earlier stage in environments considered conducive to initiation and spread of fires. In British Columbia, Nimchuk (1985) emphasizes similar factors of confirming lightning activity and correlating with other weather parameters. Lightning data are used in most provinces of Canada for forest fire purposes. Latham (1991) describes mainly positive flashes from the anvillike plume of a deliberately-set forest fire that were detected by a lightning network.

• Utilities

At the time when networks were found useful for fire detection, utilities also began employing lightning networks for operations. The Electric Power Research Institute (EPRI) supported the installation and operation of a U.S. national network. Real-time operations for utility decision makers include crew scheduling and dispatch, power load management, and outage confirmation (Orville et al., 1986a,b; Orville and Songster, 1987; Idone and Orville, 1990). Operational network data uses for utility and communications companies are in Kozak (1987); White and Driggins (1990); Whitney and Asgeirsson (1991), and Cummins et al. (1993). How lightning networks perform for utility operations has been studied in Canada (Chisholm and Janischewskyj, 1988; Vera, 1989; Herodotou et al., 1992), Germany (Fister et al., 1992), Sweden (Melin, 1991), and Switzerland (Montandon, 1992).

• Aerospace and military

1. Spacecraft operations

Lightning has major impacts on preparation and launches of spacecraft. Christian et al. (1989) describe lightning striking a rocket during launch at the Kennedy Space Center (KSC) in Florida. At KSC, studies for improved lightning nowcasting and forecasting have used surface wind convergence (Watson et al., 1987a, 1991a) and neural networks (Frankel et al., 1990; Barnes et al., 1991). SAFIR detection technology has been employed at the European Space Center on the Atlantic coast of French Guiana for lightning warnings similar to those at KSC (Richard et al., 1988; Boulay et al., 1989). The Tanegashima Space Center in Japan uses lightning detection network data for similar purposes (Kingwell et al. (1991). Network lightning is used to forecast and monitor range safety at the White Sands Missile Range (Ellison, 1992).

2. Military operations

Hunter (1988) developed synoptic-scale predictors for network lightning at an Air Force base for guidance on significant thunderstorms that influence lightning-sensitive activities. Fifth Weather Wing (1988) describes how lightning data are used by forecasters in the Air Force.

• Explosives

The mining community makes lightning warnings in areas where explosives and munitions are used; a review of lightning detection instrumentation is in Johnson et al. (1980, 1982). Network lightning data are used to support activities at the NWS Nuclear Support Office (Scott, 1989).

B. METEOROLOGICAL USES IN OPERATIONS

- **Regional monitoring and forecasting at central offices**

Two central forecasting offices for surveillance, nowcasting, and forecasting of convective weather over large regions have made operational use of network flash data. They are the National Severe Storms Forecast Center (NSSFC), National Weather Service, NOAA in Kansas City, and the Bureau of Meteorology for eastern Australia. Responsibility areas of these facilities exceed the range of a single radar. NSSFC has used flash data for several years (Edman, 1986; McCann and Matthews, 1989; Mosher, 1989; Lewis, 1989). Uses of flash data at NSSFC are in Mosher and Lewis (1990); many of the same uses for Australia are in Ryan and Gunn (1993). Results of these papers (called ML and RG) emphasize the following:

1. Most frequent applications

ML list eight aspects of convection that lightning data depict well; RG reiterate many of them (Figure 7).

Existence: The presence of lightning, and thereby thunderstorms, is usually the highest-ranked use.

Initiation: Lightning is often the first indication of the existence of a new storm.

Movement: Animation and looping of lightning maps easily follow the progress of individual storms.

Dissipation: It is important to know when a storm has ended, and sometimes difficult to determine. The end of lightning is a good indicator that deep convection has ended.

Configuration: Whether the storm is in a line, a series of isolated cells, or in diffuse organization is easily found with flashes.

Coverage: Especially on a scale larger than a single radar's scan, lightning clearly indicates locations of active storms within larger areas on satellite and radar.

Intensity: The trend of flash rate through time, especially at the start and end of a storm, can indicate the stage of the storm's life cycle. Thresholds of absolute numbers of flashes have not been found helpful so far in an operational situation.

Redevelopment: When and where flashes restart in a subsequent phase of a storm can help forecasters monitor the situation.

2. Timeliness

ML and RG found that when lightning data are available immediately, forecasters will access the data most often on the scale of seconds up to a few minutes (Figure 8). Lightning data were available for both of the studies described in ML and RG within a few seconds, since communications were made between the forecast offices and the network's central computer. In these and many other networks, satellite communications provide part or all of the data path. However, if the flash information is transmitted on fixed schedules, the delay may be as much as 15 minutes. In general, individual and volume radar scans are collected at less than 5-minute intervals. However, in practice, the radar data frequently are available to forecast offices over large regions only at 15-minute intervals, and some further delays may occur.

3. Comparisons to other data

For monitoring significant or severe weather, ML and RG report that forecasters often consider lightning data to be a better source of the existence of convection than radar returns. ML report that lightning data contributed unique information about the convective situation in 26 to 74% of the cases. RG report lightning data were important to forecasting convection during 80% of the shifts. Also, lightning provided the first notice of a thunderstorm on 58% of the shifts when convection occurred (Figure 9). RG describe the most frequent lag as 60 minutes between first lightning detection and first thunderstorm observation from other data; other data sources include surface observations, radar and satellite observations, and storm spotter reports.

4. Changes to forecasts

RG report that lightning data were used to amend forecasts in 14% of the cases. Lightning-triggered changes were most common during shifts when the forecast was incorrect. When the forecast was correct, lightning data were used to refine location and/or timing of convection forecasts. Also, the Australian forecasters often monitored the lightning data stream to be sure that no unexpected convective storms had recently formed.

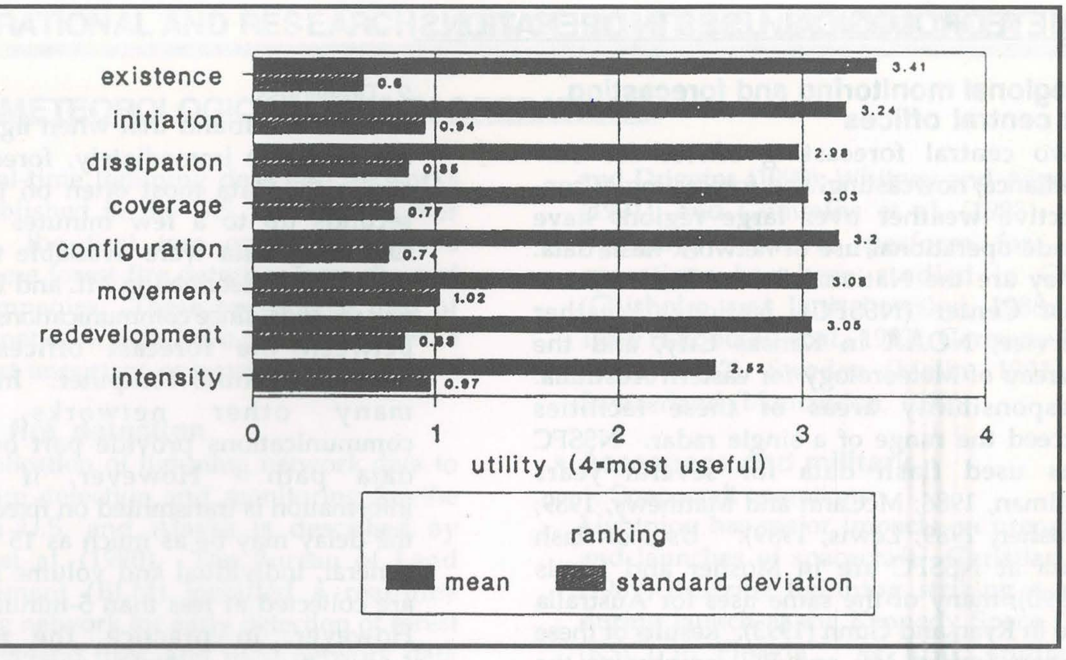

FIGURE 7. Eight most common utilities of flash data at NSSFC as ranked by forecaster at end of shift. Rank of 4 is most useful; 0 is not applicable and not used in calculations (from Mosher and Lewis, Preprints, 16th Conference on Severe Local Storms and Conference on Atmospheric Electricity, 692-697, 1990, American Meteorological Society).

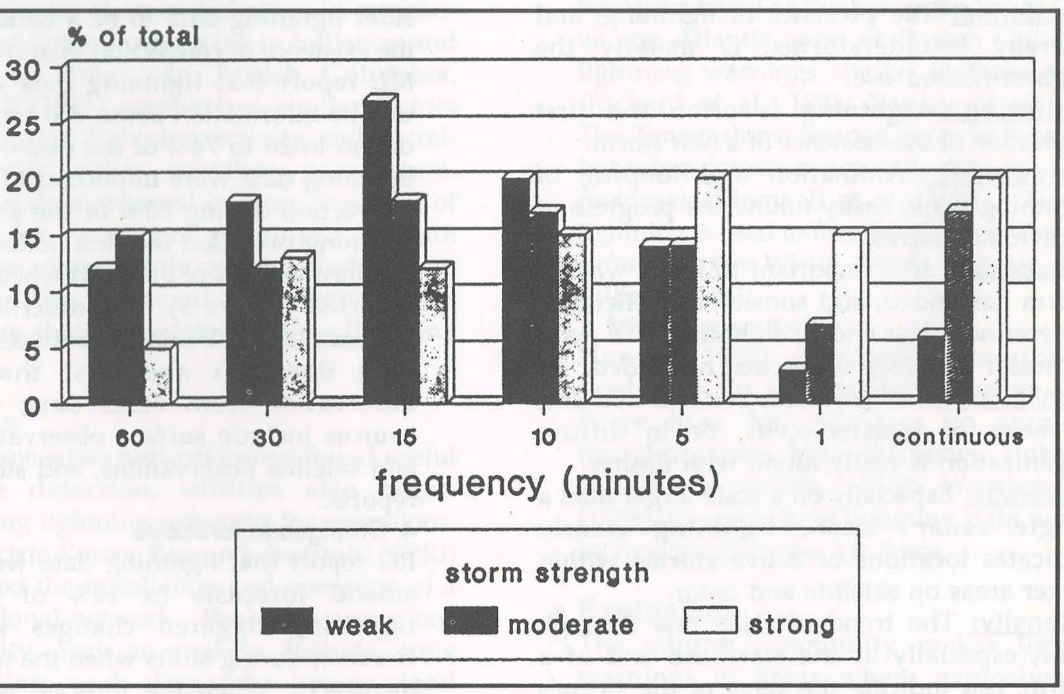

FIGURE 8. Frequency of lightning data usage by NSSFC forecasters during their busiest shift periods (from Mosher and Lewis, Preprints, 16th Conference on Severe Local storms and Conference on Atmospheric Electricity, 692-697, 1990, American Meteorological Society).

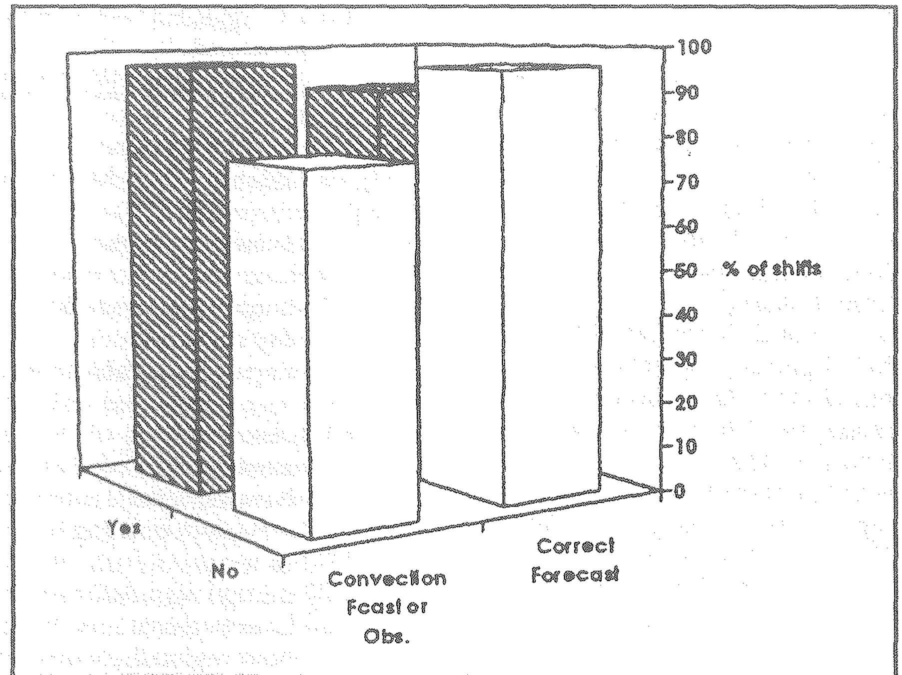

FIGURE 9. *Proportion of shifts when lightning data were used, depending on whether or not convection was forecast or observed, and when the forecasts were correct or incorrect (from Ryan and Gunn, Preprints, 17th Conference on Severe Local Storms and Conference on Atmospheric Electricity, J40-J44, 1993, American Meteorological Society).*

Monitoring and forecasting at local stations

Lightning network data have been used operationally at local weather stations for two situations. One situation was in the western U.S., where scarce radar data made lightning a popular dataset at most stations when it was introduced, and the other is at various stations outside the west.

1. Western United States

The Bureau of Land Management (BLM) deployed their lightning detection network in the western United States (Section 3A) for forest and range fire detection and warning. Shortly afterward, the National Weather Service of NOAA accessed the BLM lightning data for its operations at many local stations in the western third of the country. Uses of lightning data in this region are in Western Region (1982, 1985, 1989); Rea and Fontana (1980); Todd and Labas (1982); and Rasch and Mathewson (1984). Mielke (1990) lists these reasons for use of flash data in the region:

Radar coverage: Coverage currently is poor in the western U.S. The area will continue to have gaps when deployment of the new radar systems in the U.S. is completed.

Terrain: The mountainous terrain throughout the western states blocks radar signals in many sectors.

Surface observations: Relatively few surface sites have been located in the western U.S., although improvements will come from automated systems.

Fire weather: Since most of the western states is semi-arid or arid, many weather stations have fire weather forecast responsibility. Lightning is a major cause of forest and range fires in the region.

Convective weather forecasting: Severe thunderstorms, tornadoes, flash floods, and microbursts are problems in the west, but storms are often less intense and frequent than in some parts of the U.S.

To provide localized lightning information to operational forecasters, lightning alerts can be defined as needed by the forecaster (Mielke, 1990). The alert is generated at the regional computer facility and transmitted to the designated office. Another option provides a listing of individual lightning strikes around a user-specified location and time window. A recent example of lightning data available in real time is in Table 1.

TABLE 1. Type and frequency of lightning products generated by Western Region, National Weather Service (Mielke, 1990).

Graphics	
30-minute contours	30 minutes
30-minute individual positive flashes	30 minutes
3-hourly contours	2 hours
24-hour contours	12 hours
72-hour count versus time	8 hours
7-day contours	24 hours
7-day count vs. alarm/alert warning	As needed
Alphanumeric	
30-minute regional	30 minutes
24-hour regional	12 hours
Alarm/alert warning	As needed
Dial-in users	
30-minute regional	30 minutes
24-hour regional	12 hours
3-hour regional	2 hours
7-day regional	24 hours

2. Additional stations

Other stations have used flash data in nowcasting and forecasting projects.

Forecast offices: Gerwitz (1987); Biedinger and Stern (1989); Struthwolf (1989); Rickard (1991); and Sabones and Sharp (1991) describe operational uses of flashes in different local forecast offices to determine whether a convective cell is a thunderstorm, and the use of positive flashes to identify the life cycle of thunderstorms. Real-time flashes complement radar and surface observations for aviation and public forecasts and warnings in areas with gaps in radar coverage. Juvanon du Vachat and Cheze (1993) describe a pilot nowcasting program for Paris combining CG and total lightning.

Aviation: Ewald (1987) describes uses of flash data at a facility that provides thunderstorm advisories on the scale of 30 to 120 minutes; flashes are considered a valuable supplement to radar and satellite data. Lightning data are used at NSSFC for advisories of in-flight thunderstorms that are hazardous for aviation (McCann and Matthews, 1989); uses by NSSFC were in this section B. Lyons et al. (1989c) list features of flash data for aviation: directly identify thunderstorms, provide uniform and wide coverage, available in real time, simple to interpret, easy to animate, and warn ground crews.

C. FLASH CLIMATOLOGIES

Climatological features of cumulus convection are especially well suited for research with lightning data. It is particularly important for meteorological applications to understand the relationships of deep convection to mountains and large water bodies. Flash information is compact and appears to be unaffected in any significant way by topography. Lightning data are easier to process and manipulate than radar and satellite information for large areas and long periods. Note that the presence of lightning is the only parameter being measured; weaker convection not producing lightning also appears on radar scans and satellite imagery.

Climatological distributions of convection have been specified with lightning data in the following list and Table 2 showing the regions, seasons, and studies:

- The largest area covered by a lightning climatology based on real-time network data is the continental United States (Orville, 1991a). Further discussions of the calculation methods are in Orville (1993) and Smith (1993).
- The subtropical peninsula of Florida during summer according to relationships with coastlines and synoptic-scale flow regimes at several levels of the atmosphere (Maier et al., 1984a; López and Holle, 1986; Reap, 1993).
- The arid to semi-arid state of Arizona during the summer months (Watson et al., 1994b) by time of day and year.
- The mountainous western two-thirds of the U.S. during summers of two years (Reap, 1986).
- The states of Kansas and Oklahoma by time of year and day, and location within these states (Reap and MacGorman, 1989; MacGorman et al., 1993b).
- Portions of the eastern United States (Orville et al., 1987; Orville, 1990b); the second study was during winter.
- The mountainous state of Colorado, (López and Holle, 1986).
- The state of Alaska during summer (Reap, 1991).

TABLE 2. Number of flashes, months, and years included in published climatologies of flashes (see text).

Area / Flashes	Months/years	Reference
Entire United States		
13,400,000	12/1	Orville (1991a)
Florida		
140,000	3/1	Maier et al. (1984a)
233,000	8/1	López and Holle (1986)
6,166,612	28/4	Reap (1993)
Arizona		
3,817,000	24/6	Watson et al. (1994b)
Western United States		
2,180,000	12/2	Reap (1986)
Oklahoma, Kansas		
1,918,000	12/2	Reap & MacGorman (1989)
301,727	13/2	MacGorman et al. (1993b)
Eastern United States		
720,000	12/2	Orville (1987)
150,000	2/1	Orville (1990b)
Colorado		
104,000	12/1	López and Holle (1986)
Alaska		
82,000	15/3	Reap (1991)

These climatologies typically include:

- Time of year of lightning, usually shown by monthly distributions (Figure 10).
- Time of day of lightning (Figure 11).
- Horizontal maps of lightning; a grid of various types is developed that depends on the size of the region (Figure 12).
- Maps by time of year or time of day (Figure 13).

A wide variety of types of studies can be performed for regions with lightning data over a sufficiently long period, preferably for more than one summer or other season. For example, Westcott (1993) found that flash densities were somewhat higher over and downwind from 19 large cities in the central U.S. than upwind of the cities.

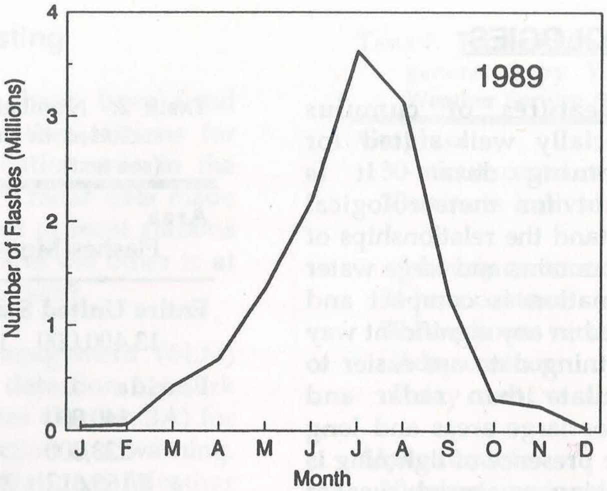

FIGURE 10. *Time of year of cloud-to-ground lightning during 1989 over United States (from Orville,* Monthly Weather Review, *119, 573-577, 1991, ©American Meteorological Society).*

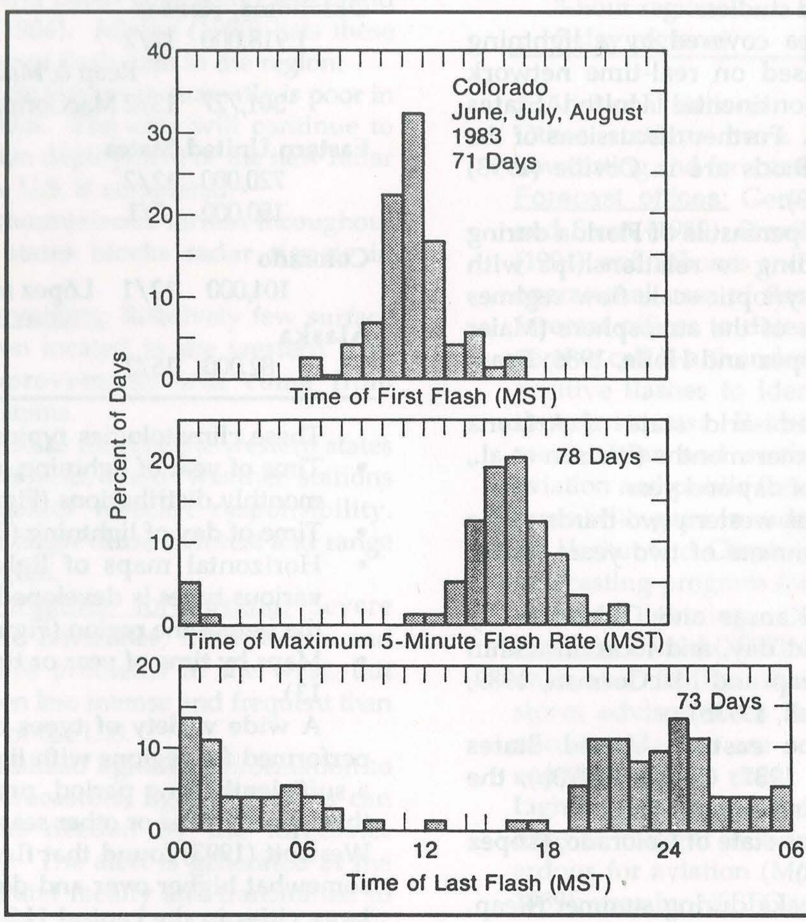

FIGURE 11. *Time of day of first, maximum rate, and last cloud-to-ground lightning in summer of 1983 over Colorado (from López and Holle,* Monthly Weather Review, *114, 1288-1312, 1986, American Meteorological Society).*

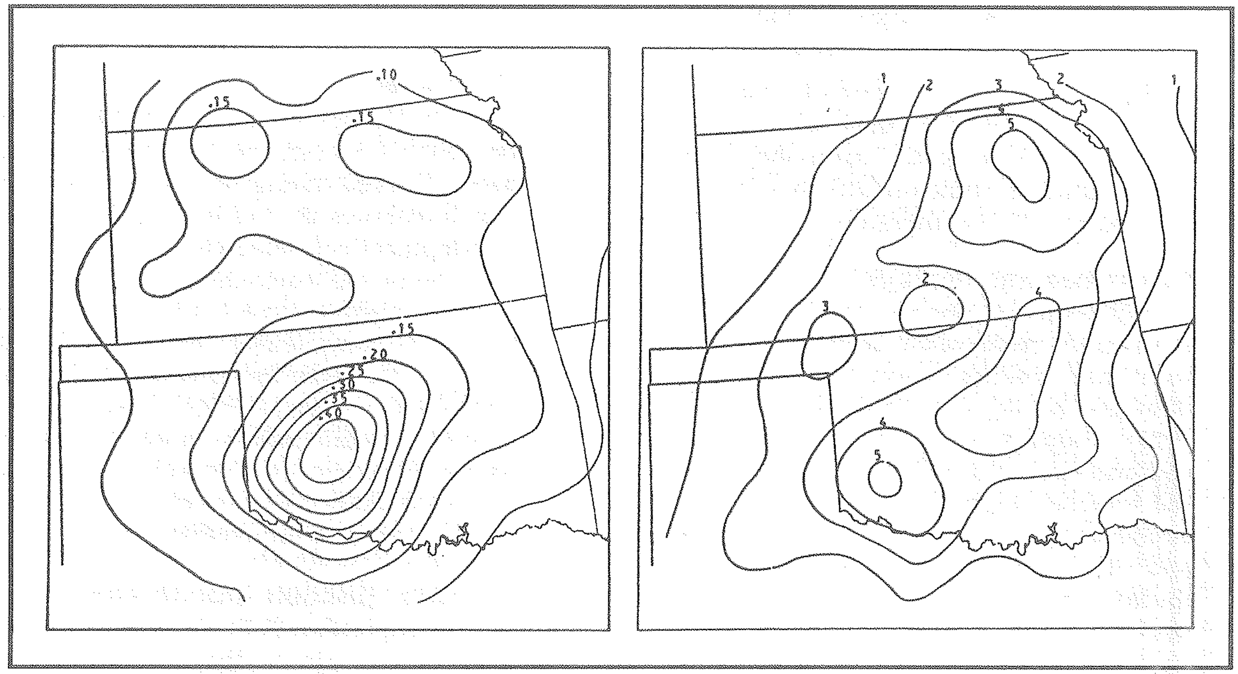

Figure 12. Maps of cloud-to-ground flash density (flashes per square km) over Oklahoma and Kansas in 1985 and 1986 warm seasons. Flashes lowering negative charge on left, and positive on right. The grid employed is 48 by 48 km (from Reap and MacGorman, Monthly Weather Review, *117, 518-535, 1989, American Meteorological Society).*

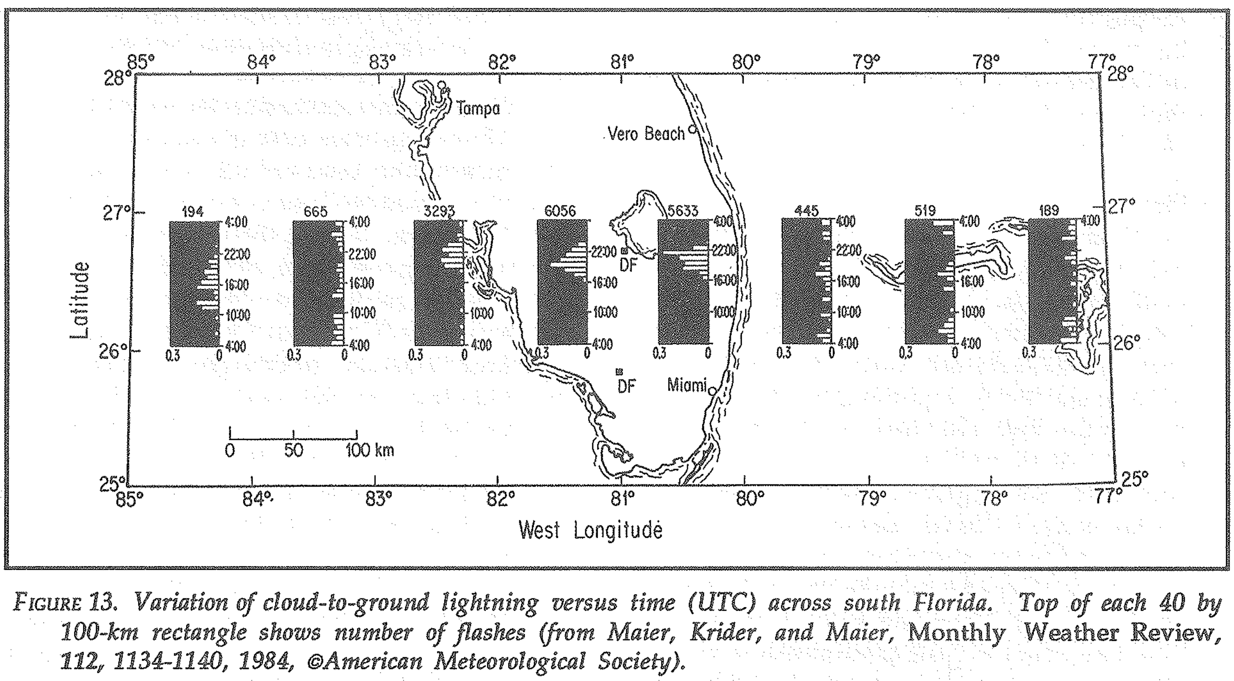

Figure 13. Variation of cloud-to-ground lightning versus time (UTC) across south Florida. Top of each 40 by 100-km rectangle shows number of flashes (from Maier, Krider, and Maier, Monthly Weather Review, *112, 1134-1140, 1984, ©American Meteorological Society).*

D. STORM-SCALE RESEARCH

Lightning detection networks have been used by meteorologists in a wide range of research on thunderstorms. Due to the emerging nature of studies, some research has only been presented in informal literature.

- **Casualties and damage**
Cloud-to-ground flashes from a Florida network were composited around locations of lightning deaths, injuries, and objects damaged on the ground (Holle et al., 1992, 1993). People were victims more often at the end and start of thunderstorms, compared to the middle. Lightning rates at the time of casualties were weak to moderate. Structures and other objects were struck more in the middle of storms with higher flash rates than for people.

- **Flash floods**
Cloud-to-ground lightning data were used by Kane (1990) to study a flash flood in Ohio associated with a mesoscale convective system (MCS); lightning data gave location, movement, redevelopment, merging, and propagation of convective cells and clusters. Lightning detection graphics similar to those in Table 1 located a maximum in flash counts that preceded flash flooding in Las Vegas, Nevada by about an hour (Cylke, 1992).

- **Hail**
In Oklahoma and Kansas, storms with large hail typically produced high densities of positive flashes (Reap and MacGorman, 1989). Hailstreaks in Illinois were always closely associated with CG lightning (Changnon, 1992). Lightning seldom occurred where the hail fell, instead it formed and moved in a 10- to 15-square km area on either the left or right forward flanks of hailstreaks. Hail severity was well correlated with the flash rate. Lightning centers developed 9 minutes before hail and 5 km backward along the storm's track from first hail, then lightning diminished shortly after hail ended (Figure 14). In Oklahoma and Illinois (MacGorman and Burgess, 1994), large hail was reported when positive ground flashes dominated, then the frequency and diameter of hail decreased after CG flashes switched mainly to negative.

- **Hurricanes**
Lightning is not commonly observed in hurricanes. However, bursts of lightning have been observed during several tropical storms and hurricanes during explosive convective development near their circulation centers, or in some of the outer or spiral rainbands as intense updrafts inject supercooled water above freezing levels (Black et al., 1986; Venne et al., 1989; Lyons et al., 1989b; Roohr and Vonder Haar, 1992). Lascody (1992) reports a circular pattern in the few lightning flashes observed by a detection network as hurricane Andrew's eye crossed the warm Gulf Stream of south Florida.

- **Low-precipitation thunderstorms**
Low-precipitation (LP) thunderstorms have little or no rain at the surface, but may produce large hail and weak to moderate tornadoes. They typically develop near a dryline and have a single strong updraft, but no surface downdraft. Mainly positive flashes occur during the LP phase (Curran and Rust, 1992; Branick and Doswell, 1992), then more negative flashes occur as the storm splits or merges with other storms.

- **Mesoscale convective systems**
Mesoscale convective systems (MCS) and mesoscale convective complexes (MCC) sometimes produce as many as 40,000 or more CG flashes during their lifetime. They often have higher ratios of positive flashes than smaller convective weather systems. Time series of CG flashes were compared to radar and aircraft overflight information by Goodman (1983), and to satellite-based life cycles by Goodman and MacGorman (1986) and López et al. (1990b); MCCs can have flash rates over 3000 flashes per hour or 60 flashes per minute (Figure 15). CG lightning in MCSs has been related to rainfall (Nielsen et al., 1990; Holle et al., 1994), radar (Kane, 1993); and severe weather (McCollum and Maddox, 1993). Network CG strikes have been related to MCS microphysical and dynamic structure, and electrification processes (Rutledge and MacGorman, 1988, 1989; Rutledge et al., 1990, 1993; Schuur et al., 1990, 1991; Keighton et al., 1991; Hunter et al., 1992).

- **Microbursts**

Lightning-microburst studies have emphasized time scales of minutes, since downbursts and microbursts are short-lived storm-scale phenomena (Williams et al., 1989a). CG lightning can typically identify a microburst (Buechler et al., 1988) through time trends in positive ratios and total flashes. However, to detect precursors to microbursts of up to 10 minutes or more for airport operations, systems that detect both cloud and CG flashes such as SAFIR have promise (Goodman et al., 1988c, 1989; Buechler et al., 1988, 1989; Laroche et al., 1991a,b). Microbursts derive from parent clouds with tops colder than freezing, thus they have an ice phase and some lightning (Williams, 1990). Microbursts that occur in dry environments typically have fewer flashes than those in moist environments.

- **Positive/negative polarities**

Networks with the capability of detecting CG flashes lowering positive charge to ground became available in real time during the 1980s. Most lightning-network studies now include the positive-flash component in their analyses or have positive flashes as their principal component (Engholm, 1988; Brock, 1991). Thunderstorms starting with more flashes lowering negative charge to ground (Figure 16), and ending with higher ratios of positive flashes were documented by Orville et al. (1988) and Stolzenburg (1988), and discussed by Hill (1988). As mentioned earlier, MCSs have higher positive flash ratios in the stratiform regions late in their life cycle (López et al., 1989c; Rutledge et al., 1990; Holle et al., 1994). In contrast, there are more positive flashes early in the life cycle of most low-precipitation storms (Curran and Rust, 1992; Branick and Doswell, 1992), some severe storms (Helsdon, 1990), and some tornadoes and supercells (MacGorman et al., 1989; Knapp, 1992a,b; Seimon, 1993; MacGorman and Burgess, 1994 later in this section). For most nonsevere thunderstorms, positive flashes are associated with weaker reflectivity than negative CG flashes (López et al., 1989c; Reap and MacGorman, 1989; MacGorman and Nielsen, 1991). How flashes of both polarities relate to VIL and echo tops is shown by Watson and Holle (1994).

- **Radar echoes**

Lightning does not necessarily coincide with highest radar reflectivity, but the data are complementary. This summary of radar-lightning comparisons proceeds from larger to smaller scales. Results differ due to variations between storms, or between analysis intervals in space and time.

1. One hour or more

During heavy rain lasting several days in summer over Alaska, Fathauer (1984) found CG lightning on the fringe of the raining clouds. In Massachusetts, most flashes were ahead of intensifying cells in a squall line of weak echoes (Geotis and Orville, 1983). For storms over an hour, rain volume per flash in Florida decreases as buoyancy increases (Buechler et al., 1990; Goodman and Buechler, 1990; Buechler and Goodman, 1991). Similar relations with instability were found for Florida (López et al., 1991a) and Australia (Rutledge et al., 1991). Hourly data in Oklahoma and Kansas (Reap and MacGorman, 1989) and the western USA (Reap, 1986) show that when *maximum point* reflectivity increases in a 48-km grid square, the probability of two or more CG flashes increases (Figure 17). Many grid squares had flashes with peak reflectivities below 40 dBz, although this level is used to identify thunderstorms. Over Florida, morning and night echoes have rain but few flashes, while afternoon rain is the inverse (López et al., 1986).

2. Less than one hour

Comparing lightning and radar data on scales of a few minutes and km, the most frequent base-scan reflectivities with lightning are around 40 dBz. In Florida (Figure 18), few CG flashes were at reflectivities above 50 dBz, and flashes decrease below 40 dBz (Holle et al., 1983, 1984; Watson et al., 1989b). In Colorado, storms with moderate echoes produced more negative flashes than storms with high reflectivities that also have more positive flashes (López et al., 1990a). In Michigan, Kane (1993) shows lightning relative to reflectivity at several levels. In Oklahoma, Watson and Holle (1994) showed that lightning presence was most often associated with weak Vertically Integrated Liquid values in a squall line on a 4-km grid per 5 minutes.

- **Rainfall**

Few studies have compared rain from gauges to network flashes. In Sweden, the ratio of positive to total flashes from a network decreased with more precipitation from gauges (Murty et al., 1983). Over New Mexico, heavy rain began at the time of peak lightning, and maximum rain occurred 45 minutes after peak lightning (Ellison, 1992). Over Arizona, days with measurable precipitation related well (Figure 19) with lightning (Watson et al., 1994b); note that these results do not show amount, but presence of any rain on a day.

- **Small thunderstorms**

The lightning threat from small but common thunderstorms is important for warning and safety issues, in view of the casualty and damage results mentioned earlier. In Florida, the mean distance between successive CG flashes in a small thunderstorm ranged from 3 to 4 km (Krider, 1988). For Kennedy Space Center operations, the lightning hazard from small storms is a major problem (Nicholson et al., 1988).

- **Squall lines**

In a squall line in Massachusetts, a detection network located lightning in the forward peripheral regions rather than in or near the cores (Geotis and Orville, 1983). Many squall lines also have an earlier stage with severe weather and/or a trailing stratiform region later in the life cycle. For example, Nielsen et al. (1994) describe lightning in a squall line in Kansas and Oklahoma that began by producing severe weather and high positive flash ratios, then the positive ratio decreased, and finally the ratio increased again as the trailing stratiform region developed. Network lightning data were used by Rutledge et al. (1991) and Schuur et al. (1991) to study electrification in the trailing stratiform region behind squall lines near Australia and in Oklahoma. In an Oklahoma convective line with severe weather, network lightning of both polarities was related by Watson and Holle (1994) to VIL and echo tops on small scales.

- **Thunderstorm observations**

There are two motivations for comparing lightning network data with human observations of thunder.

1. Thunder-day climatologies

One motivation is to replace thunder-day climatologies, the number of days with thunder at a site. Thunder days have long been used for design and protection of ground facilities. The latest thunder-day, thunder event, and duration data for the USA are by MacGorman et al. (1984a). Changnon et al. (1988) found that values of thunder events do not relate well to CG flash frequencies from networks, and actual storm activity is underestimated by thunder day and event records. Reasons include: observers not hearing the thunder from the lightning observed by the network, the inverse, the tendency for lightning distributions to be skewed during thunderstorms, and location errors in detection systems. Changnon (1989) compared thunder observations with CG network flashes in the United States (Figure 20) although general trends exist, relationships are not uniform between regions. Errors are considered minimal in the flash data, but errors in thunder events are sizable. Clodman and Chisholm (1993) emphasized that a few storms can dominate lightning samples.

2. Automatic thunderstorm identification

The other motivation for comparison studies is to use lightning networks for thunderstorm identification at automatic weather stations. McNulty et al. (1990) address operational issues in human versus network detection of thunderstorms. Reap and Orville (1990) related human observer records and CG network data in the northeast USA. Storms were detected by both methods during less than half the time with a 16-km search radius, compared to 82% within a 50-km radius. Reap (1992) compared observer records and CG lightning network data. As lightning frequency increased, the probability of the thunderstorm being detected by both methods also increased. And, as the radius of search with the lightning data increased, the human observer was more likely to hear the storm.

• Thunderstorm tops

As top heights increased for Florida storms (Holle and Maier, 1982), the probability of lightning within 5 minutes and 10 km of the radar top measurement increases from 10% for tops under 9 km to 100% over 17 km. In a very large MCS over Michigan and adjacent Great Lakes (Kane, 1993), the largest area of echo tops above 14 km peaked an hour before the maximum 10-minute CG flash rate. In Oklahoma, lightning was most often associated with radar-measured tops in the 25,000- to 45,000-foot range within 4 km and 5 minutes of radar measurements (Watson and Holle, 1994).

• Tornadoes and severe weather

1. Case studies

In the northeastern U.S., peak lightning rates preceded tornadoes by 10 to 15 minutes, then CG rates declined (Kane, 1991). Much of the recent severe-storm research has shown more positive flashes before and during tornadoes and severe storms than afterwards. During a very strong tornado in Oklahoma, positive flash ratios were high throughout the storm; cloud lightning measured by other sensors was inversely correlated with network-measured CG flashes; and CG flash rates were negatively correlated with cyclonic shear of the parent mesocyclone (MacGorman et al., 1989). For another Oklahoma tornado, positive CG flashes started just before, and reached a peak during the tornado stage (MacGorman and Nielsen, 1991). In a severe thunderstorm in North Dakota, there were mostly positive flashes during the first 1-2 hours of several cells (Helsdon, 1990). On the northern Great Plains, low-precipitation supercell storms showed a positive-flash signature, but storms to the south with heavy precipitation had mainly negative flashes (Branick and Doswell, 1992). In Illinois, mostly positive CG flashes occurred near the storm's reflectivity core before a very strong tornado (Figure 21), followed by a lull in lightning during the tornado, then a reversal to mostly negative flashes (Seimon, 1993). In Oklahoma and Illinois, MacGorman and Burgess (1994) show a polarity reversal in a classic supercell storm before it became a heavy-precipitation supercell storm (Figure 22); while storms with high positive CG flash rates are more likely to produce severe weather than storms without high positive rates, severe weather also occurs in storms dominated by negative flashes. The positive-flash signal was used at a television station in Oklahoma to help identify and warn of a strong tornado (Shore and Lane, 1993).

2. Large samples

Hourly CG flashes were correlated with severe storms in 48-km grid squares over Oklahoma and Kansas (Reap and MacGorman, 1989). For the rare times when positive flash rates exceed 30 per hour in a square, the probability of severe weather, becomes significant. In contrast, negative flash rates can exceed 200 per hour before reaching the probability of severe weather shown by positive rates of 30 an hour. A forecasting technique for severe and tornadic storms across the United States by Knapp (1992a,b) targeted thunderstorm cells that were dominated by positive CG strikes. When a region was identified by synoptic and mesoscale analyses as having a severe weather threat over the next few hours, and positive-dominated storms were identified on lightning maps, the location subsequently had severe weather or tornadoes more than half the time. Positive flashes dominated about one-fourth of all severe thunderstorms.

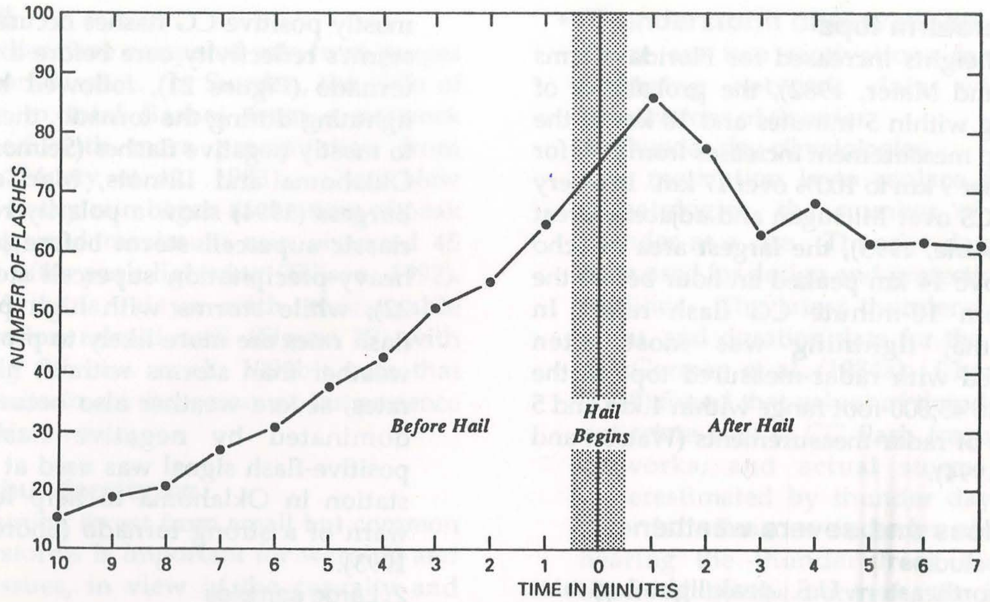

FIGURE 14. Temporal distribution of all cloud-to-ground flashes associated with 48 hailstreaks in Illinois during June and July 1989 (from Changnon, Journal of Applied Meteorology, *31, 587-604, 1992, ©American Meteorological Society).*

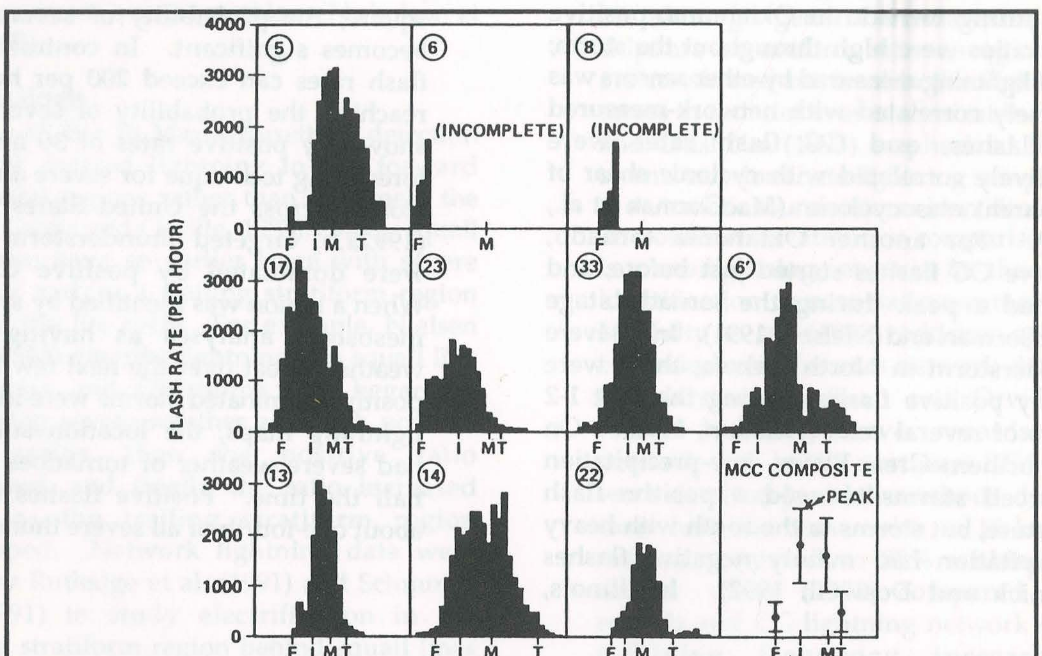

FIGURE 15. Composite cloud-to-ground lightning in MCCs based on satellite life cycles. Numbers in circles identify MCCs of study. F=first storm on satellite, I=initiation of storm, M=maximum extent on satellite, T=termination stage (from Goodman and MacGorman, Monthly Weather Review, *114, 2320-2328, 1986, ©American Meteorological Society).*

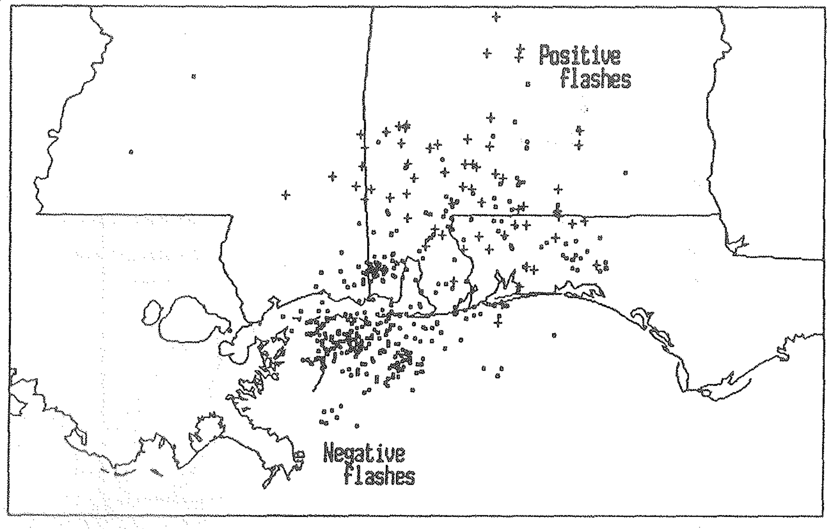

FIGURE 16. Positive CG flashes shown by plus signs and negative flashes by squares during one hour on 22 February 1987 along the Gulf of Mexico coast of the USA (from Orville, Henderson, and Bosart, Geophysical Research Letters, *15, 129-132, 1988, ©American Geophysical Union).*

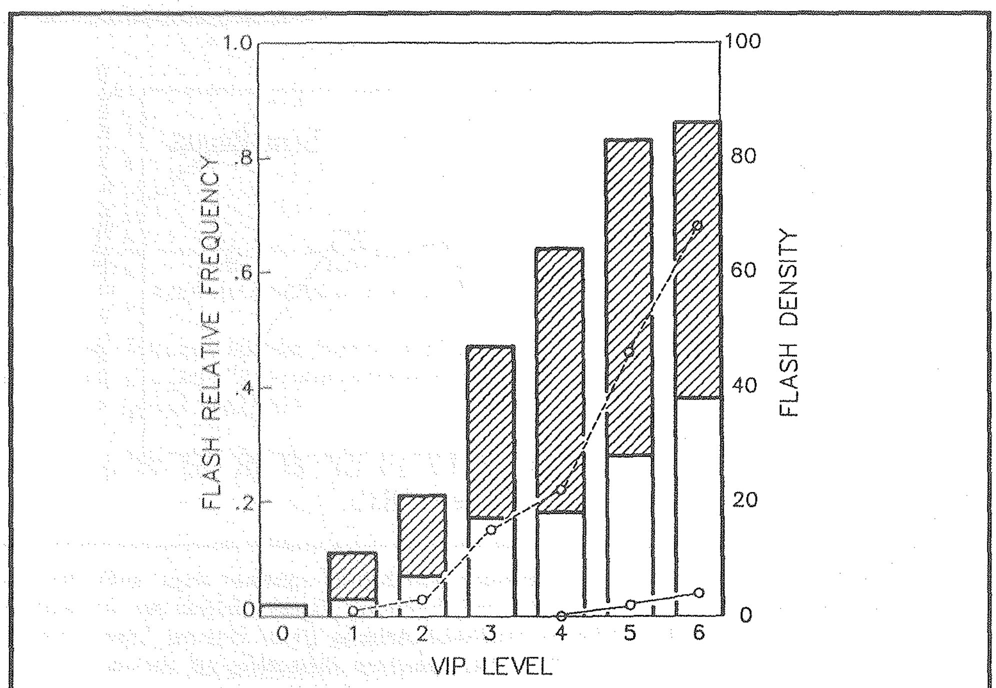

FIGURE 17. Fraction of hourly 48-km grid squares with two or more positive (clear bars) or negative (hatched) CG flashes versus maximum reflectivity in grid square over Oklahoma and Kansas. Solid and dashed lines show mean hourly density of positive and negative flashes. VIP level 1=18 to 29 dBz; 2=30 to 40; 3=41 to 45; 4=46 to 49; 5=50 to 56; 6=> 57 dBz (from Reap and MacGorman, Monthly Weather Review, *117, 518-535, 1989, American Meteorological Society).*

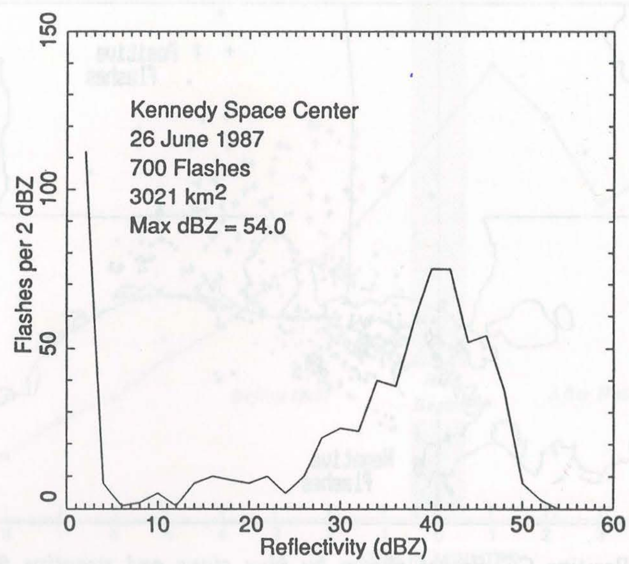

FIGURE 18. Fraction of 5-minute 1-km grid squares with negative CG flashes versus radar reflectivity over Florida (from Watson, López, Daugherty, Ortiz, and Holle, Preprints, 24th Conference on Radar Meteorology, 126-129, 1989, American Meteorological Society).

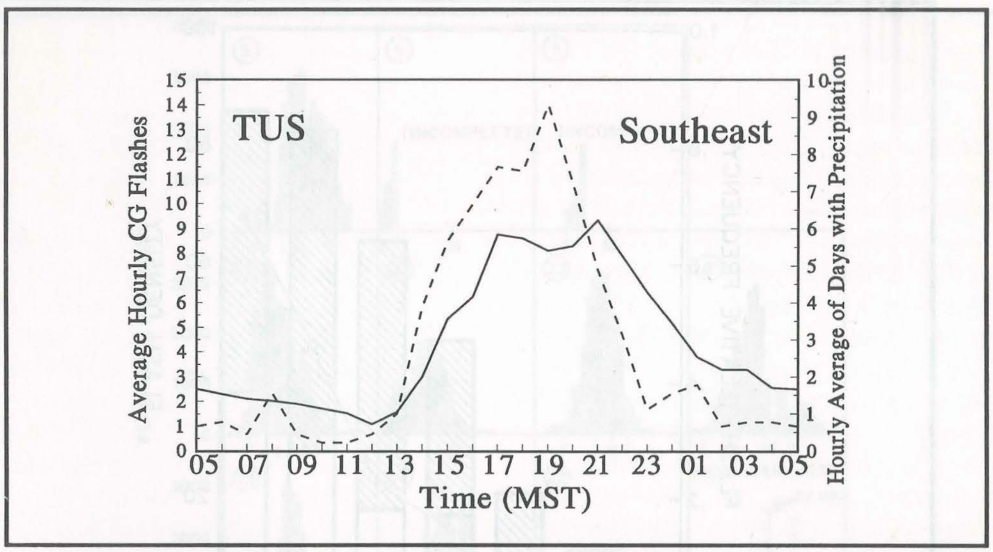

FIGURE 19. Hourly variation of average number of summer days with measurable precipitation (solid) for 1948-1990, and lightning flashes (dotted) per 400 square km per summer from 1985-1990 in southeast Arizona (from Watson, López, and Holle, Monthly Weather Review, *122, 1994, American Meteorological Society).*

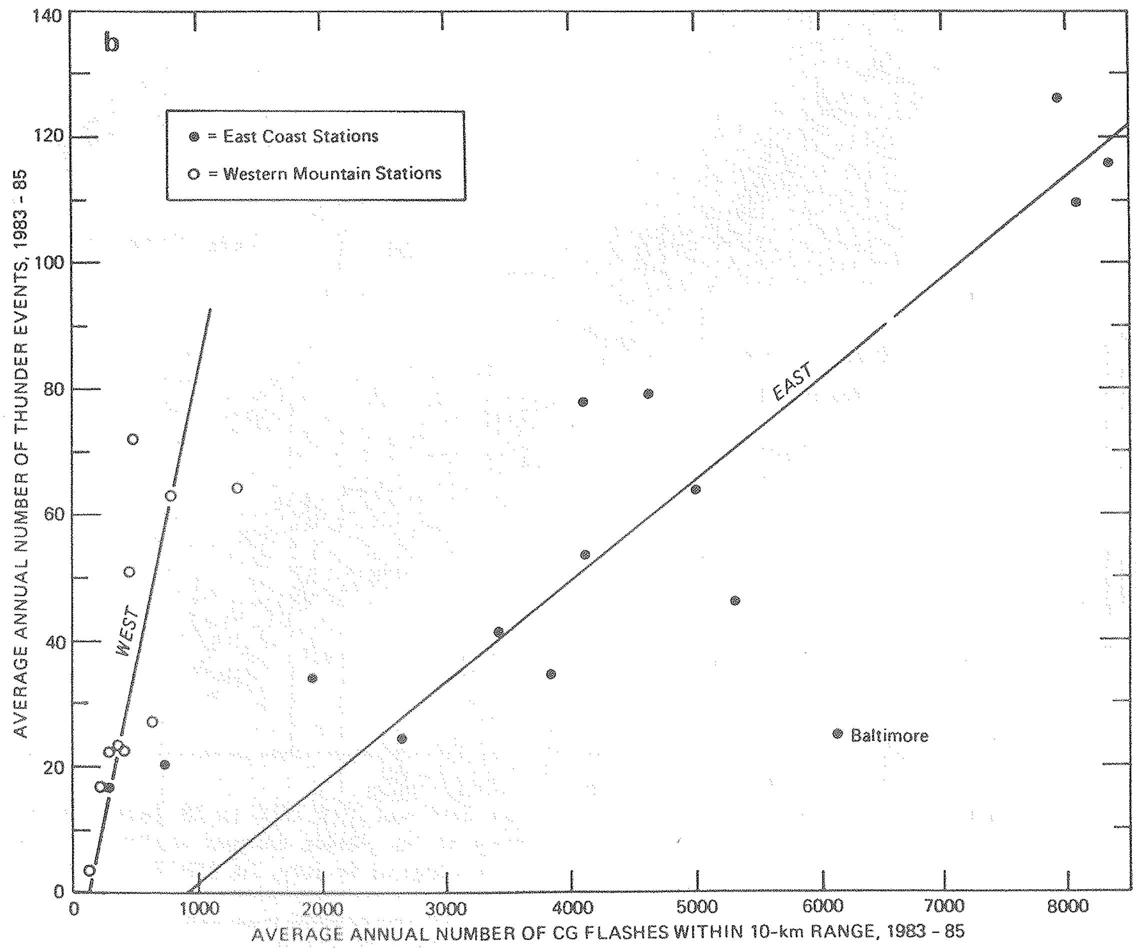

FIGURE 20. Relationships between thunder events at 25 observing stations in the eastern and western United States, and lightning from CG flash detection networks (from Changnon, Journal of Climate, *2, 897-921, 1989, ©American Meteorological Society).*

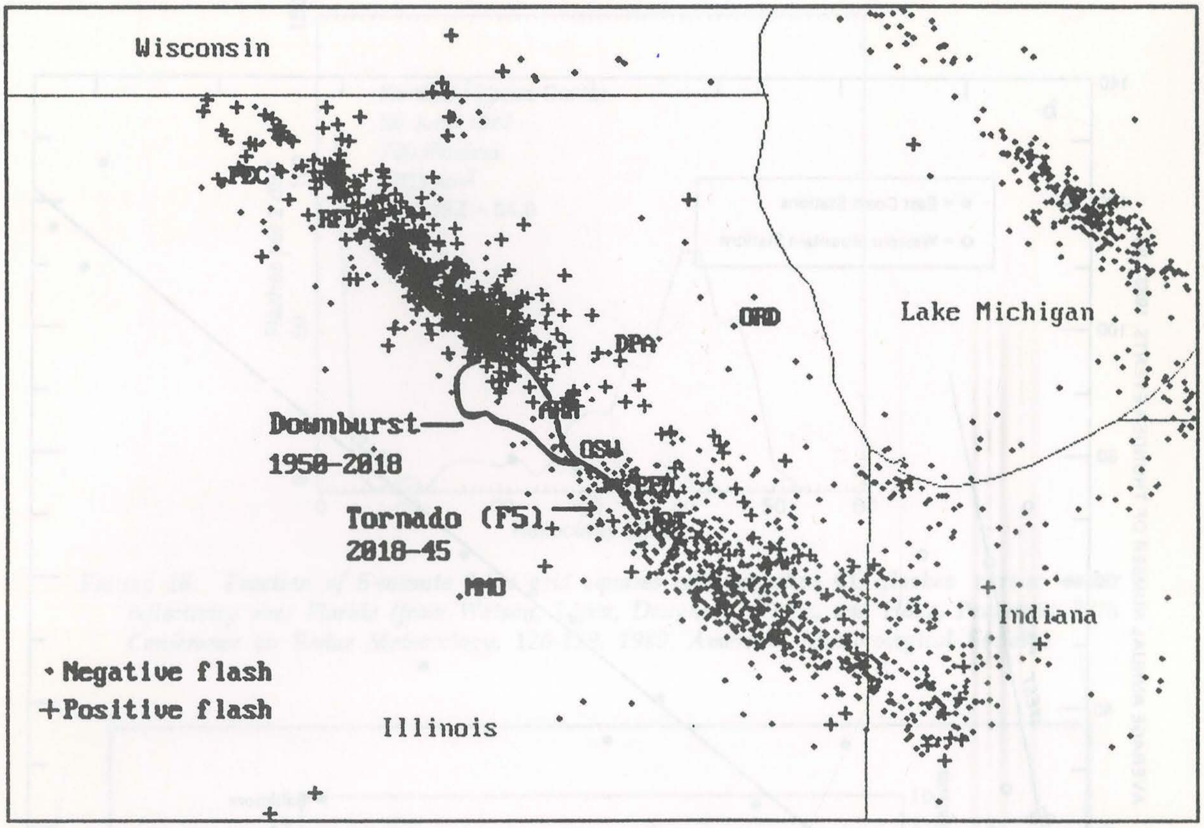

FIGURE 21. *CG lightning over lower Great Lakes region between 1800 and 2200 UTC on 28 August 1990. Positiv flashes shown by plus signs, negatives by dots as polarity of the flashes changed at time of tornado an downburst (from Seimon,* Bulletin of the American Meteorological Society, *74, 189-203, 1993, ©America Meteorological Society).*

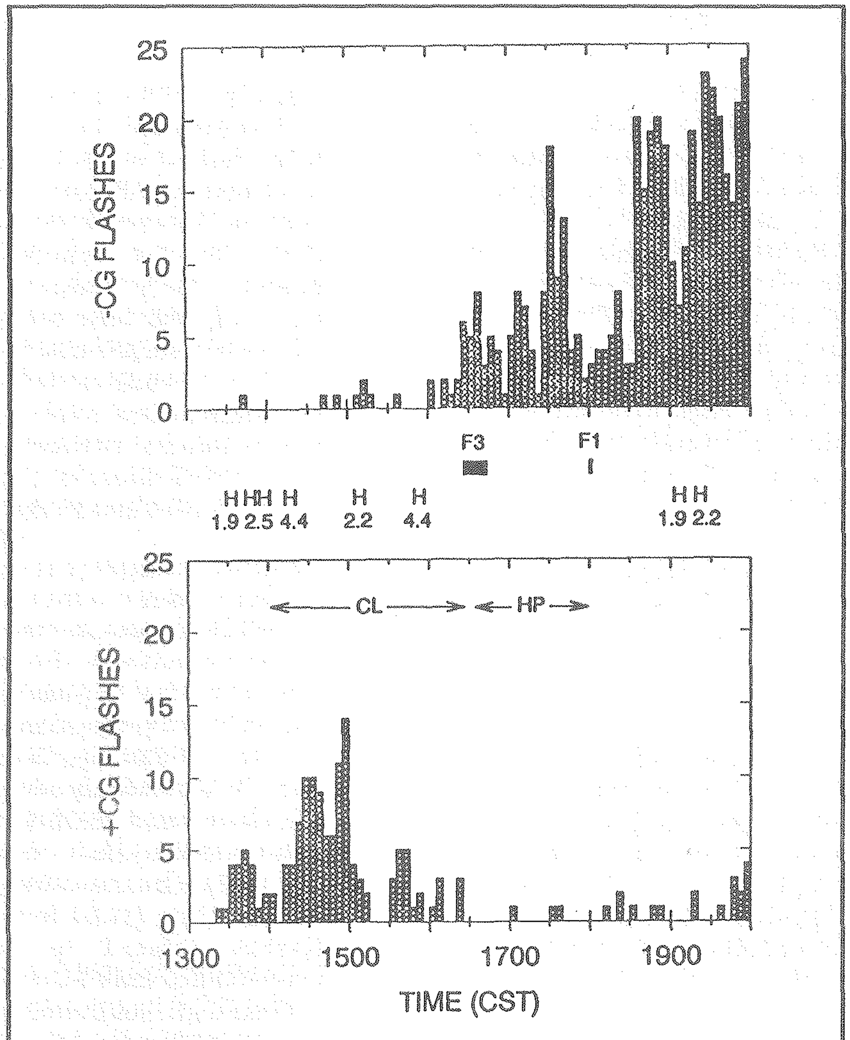

Figure 22. Time series of positive and negative CG network flashes during storm that produced a tornado in Oklahoma. H at times of large hail reports; F1 and F3 at times of tornadoes identified with the Fujita intensity scale. CL=time of classic supercell; HP=time of high-precipitation storm (from MacGorman and Burgess, Monthly Weather Review, *122, 1994, American Meteorological Society).*

E. ADDITIONAL RESEARCH

- **Coasts and lake shores**

Network data were used to develop lightning climatologies of the sea breeze zones over Florida by Maier et al. (1984a) and López and Holle (1986). Lightning data have also been used for verification of numerical model forecasts of the Florida sea breezes (Lyons et al., 1987, 1992a,b; Lyons and Pielke, 1988). Both lightning and model data were combined to study the Florida sea breeze by Lyons et al. (1990). High lightning activity has been found in rainbands over the warm Gulf Stream (Figure 23) off the east coast during northwesterly offshore flow during winter (Biswas and Hobbs, 1990; Orville, 1990b, 1993; Dodge and Burpee, 1993). Low frequencies of positive flashes were found by Moore and Orville (1990) at the downstream ends of the Great Lakes.

- **Complex terrain**

Lightning was not found preferentially at the highest altitudes, but on the slopes of mountains and ridges facing the low-level moisture flow using lightning data on a grid scale of 11 by 14 km in Colorado (López and Holle, 1986). However, in the western U.S., using a grid scale of hundreds of km, lightning was found to be directly over the highest terrain (Reap, 1986).

- **Monsoon convection**

During the summer monsoon along the north coast of Australia, CG lightning data were used to study deep convection and electrical features of squall lines during a field project by Williams and Rutledge (1990); Williams et al. (1990); Rutledge et al. (1991); and Williams (1991). Cloud-to-ground lightning data were used by Watson et al. (1994a) to study synoptic patterns that cause lightning variability during the monsoon over the southwestern United States and northwestern Mexico during summer and early autumn.

- **Numerical models**

Lightning data identified convection during the deepening of a midlatitude cyclone that was handled poorly by operational numerical models (Orville et al., 1983a). For Oklahoma and Kansas, analyzed fields from two synoptic-scale models showed that of many possible variables, surface vorticity and strong upward vertical motions were better related to CG lightning than freezing-level height and vertical wind shear (Reap and MacGorman, 1989). Over Alaska, Reap (1991) used a synoptic-scale numerical model's daily output to relate to CG lightning; the best correlations were with large-scale static instability, and local wind maxima or moisture convergence. Mesoscale numerical models were used in an operational test to forecast network-detected flashes in Florida sea breezes (Lyons et al., 1987, 1992a,b; Lyons and Pielke, 1988).

- **Satellite imagery**

1. Case studies

In British Columbia, the greatest lightning concentration was directly underneath or close to coldest (highest) infrared cloud tops and cellular convection on visual imagery (Jackson, 1982). In Oklahoma, CG flashes were in a relatively narrow line under the coldest infrared cloud tops compared to the entire cloud system on satellite (Orville et al., 1982). In the central U.S., Roohr and Vonder Haar (1992) found a sharp peak in flashes related to satellite infrared temperatures for a 5-minute period of a well-defined north-south cold front.

2. Large samples

In the western U.S., Reap (1986) compared CG lightning in a 48-km square grid on 101 days to satellite data. There was a sharp peak in lightning activity within a narrow range of high visible-cloud brightness. The distribution of lightning strikes as a function of infrared cloud-top temperatures was similar (Figure 24). For the southeastern U.S., Goodman et al. (1988a) found convective tendencies from a combination of 5-minute infrared satellite temperatures and CG flashes. Better short-term storm trends were provided by the combination than by infrared temperatures alone, except for mesoscale convective systems due to their large cirrus shields. In the western U.S., satellite data were used to estimate the ratio of cloud flashes to cloud-to-ground flashes (Price and Rind, 1993a).

- **Synoptic influences**

1. Upper-air soundings

In south Florida, differences in the local vertical profiles of temperature, wind direction, and moisture from morning soundings were related to changes in frequency of CG flashes (López et al., 1984). In central Florida, the locations and frequencies of flashes were strongly influenced by the low-level flow direction from upper-air soundings (López and Holle, 1987a,c). In Alberta, lightning that occurred later in the day was rather weakly correlated with convective instability, low-level moisture, and surface heating in the morning upper-air soundings (Anderson and Charlton, 1990).

2. Synoptic patterns

For coastal California where CG flashes are relatively rare, a temperature of -20°C at 500 millibars on the local sounding was somewhat indicative of lightning; expanding the study to include synoptic conditions gave limited success in a prototype study (Hunter, 1988). During the southwest U.S. monsoon, Watson et al. (1994a) associated high and low daily CG flash frequencies with corresponding average surface and upper-air flow regimes.

- **Tropical and subtropical convection**

Uses and characteristics of lightning network data in tropical and subtropical regions have been described earlier in Operational Uses (Section 3B), Flash Climatologies (Section 3C), Storm-scale Research (Section 3D), and this section on Additional Research (Section 3E). Almost all of the studies have been done for Florida, except for the monsoon convection studies in the Australian region.

- **Winter weather**

1. Eastern U.S. coast

More winter lightning studies have been conducted for the region off the east coast than any other location. Williams (1988) found mostly positive flashes in a long precipitation band; positive CGs did not cluster at a scale comparable to the size of an isolated thunderstorm cell as they do in summer. Biswas and Hobbs (1990) and Orville (1990b) described lightning over the Gulf Stream (Figure 23). Dodge and Burpee (1993) found that 99% of the CG lightning was detected during rainband cases, which are defined as at least 90 km in length and last 2 hours or more; the rainbands were most often in the warm sectors of fronts.

2. Other locations

During mid-winter in Florida, Williams et al. (1989c) describe the complex nature of CG flashes detected by a network as a front passed through the area. To the west of, and over portions of Japan, lightning-producing convection forms during winter as cold continental air flows across the warmer ocean on the way to Japan. Goto et al. (1992) found fewer negative flashes in winter, and attributed this to low cloud tops. Characteristics of the flashes were more like those of the mature and/or dissipating stages of summer thunderstorms. During an intense, wide-spread snowstorm over the eastern U.S., Orville (1993) found very high CG flash rates, and positive flashes accounted for 13% of all flashes from the storm. Peak flash rates occurred in the warmer air to the south during the growth stage, then the positive ratio exceeded 60% to the north as lightning from the storm ended.

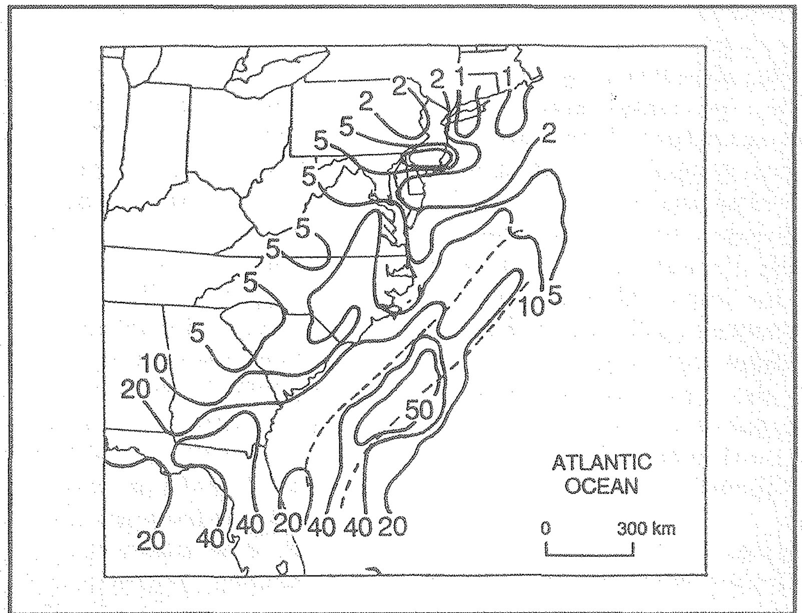

Figure 23. Isopleths of the number of CG flashes per day off the U.S. southeast coast from 15 January to 15 March 1986. Mean location of Gulf Stream was within dashed lines (from Biswas and Hobbs, Geophysical Research Letters, *17, 941-943, 1990, ©American Geophysical Union).*

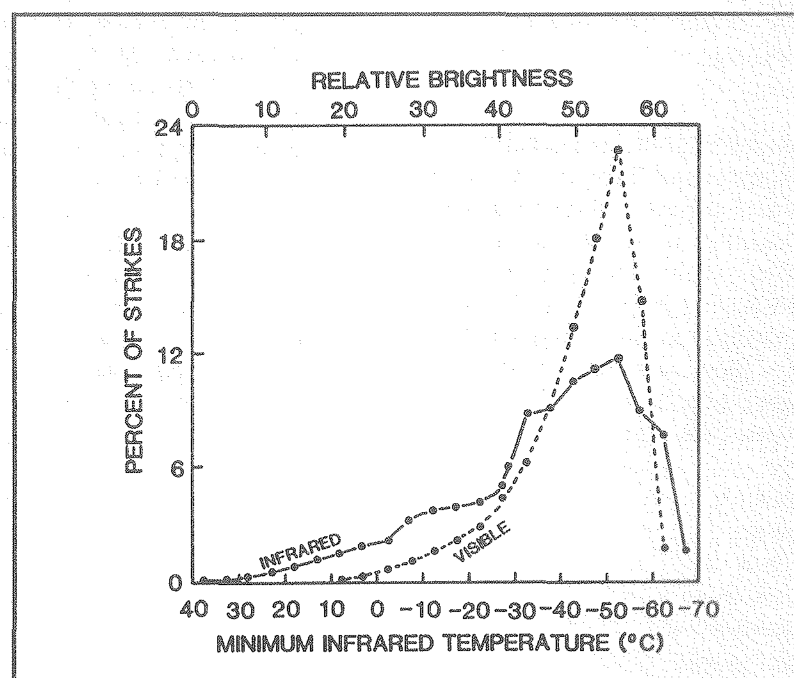

Figure 24. Distribution of lightning strikes during daylight hours of two summers as a function of satellite-based minimum infrared cloud-top temperature and relative visible brightness (from Reap, Journal of Climate and Applied Meteorology, *25, 785-799, 1986, American Meteorological Society).*

F. SAMPLE FLASH MAPS FROM LIGHTNING NETWORKS

A variety of meteorological situations is shown by the following set of flash maps detected by lightning networks.

- **Warm seasons**

Flashes over most states, and parts of Canada and Mexico are in Figure 25 on a summer day. A total of 43,776 flashes were detected from 2129 UTC on 01 August to 1257 UTC on 02 August 1989. Cloud-to-ground flashes are found over the mountainous western states in association with the monsoon, across lower latitudes with abundant low-level moisture, and across the northern regions associated with traveling upper-air disturbances. On another summer day (Figure 26), a connected line of flashes extends from Mexico to Canada from 1917 UTC on 25 August to 1248 UTC on 26 August 1993. The 44,975 flashes are mainly along a front, over elevated terrain of the intermountain western states, and in moist air over the southeastern states. Over Florida, lightning in Figure 27 locates sea breezes on the east and west coasts for 24 hours ending at 2141 UTC on 08 August 1990. Over central Florida, Figure 28 shows individual lightning-producing storms for 24 hours ending at 2234 UTC on 6 May 1991.

- **Mesoscale convective systems**

In late spring, flashes were organized into several large MCSs. Figure 29 shows the flash-by-flash depiction of 44,991 flashes in the area, while Figure 30 shows the same flashes in an operational contour data presentation from 0212 to 1451 UTC on 05 June 1992. A single MCS moving northwest to southeast is in Figure 31. There were 20,186 flashes during the 24 hours ending at 0128 UTC on 22 May 1989.

- **Cold seasons**

In late winter, the lightning map in Figure 32 shows three separate areas of synoptic-scale forcing that are strong enough to produce lightning from thunderstorms. For this map, there were 868 flashes across the United States during the 24-hour period ending at 1501 UTC on 5 March 1990. One area of forcing is over the western states, one is over the central plains, and one is leaving the southeast coast. Another interesting feature is that lightning has been observed by detection networks to be organized on large scales and in orientations that were not previously known from surface stations and other available datasets. A straight east-west line of flashes located along a warm front over the southern Great Lakes region is shown in Figure 33. The time period is for the 24 hours ending at 1343 UTC on 17 April 1991. Another day with numerous long lines occurred during the 24 hours ending on 21 December 1990 at 1548 UTC (Figure 34). It has been observed that large areas with large numbers of flashes during colder months of the year can indicate significant weather. Figure 35 shows 44,080 flashes during a portion of a major outbreak of tornadoes, wind and hail across the southeastern U.S. states during the period from 1600 UTC on 15 November to 1357 UTC on 16 November 1989. On the previous day, there were 14,500 flashes associated with this synoptic-scale system to the west of the area on this map. A north-south cold front in the middle of the United States, and an east-west warm front across the southern Great Lakes are both apparent in the map of Figure 36. For this map, a total of 19,517 flashes was detected from 1942 UTC on 10 March to 1441 UTC on 11 March 1990.

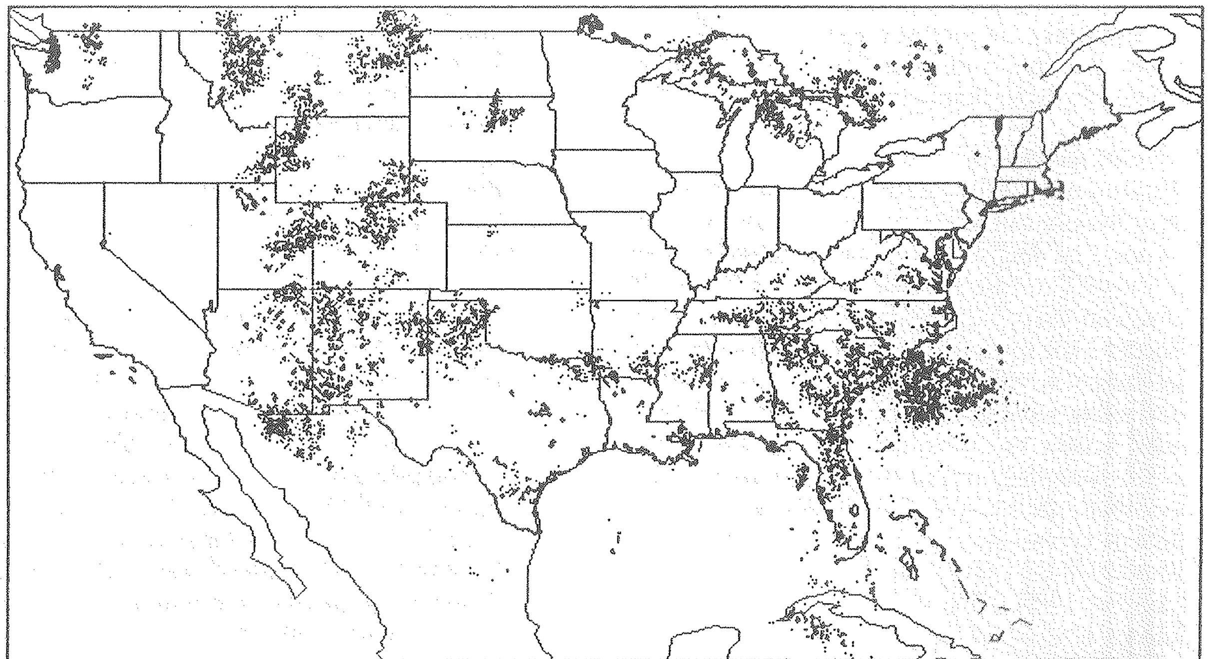

FIGURE 25. *Map of 43,776 CG flashes detected by a real-time network during less than 16 hours on a summer day over the continental United States and adjacent regions. Dots are flashes lowering negative charge, plus signs for flashes lowering positive charge.*

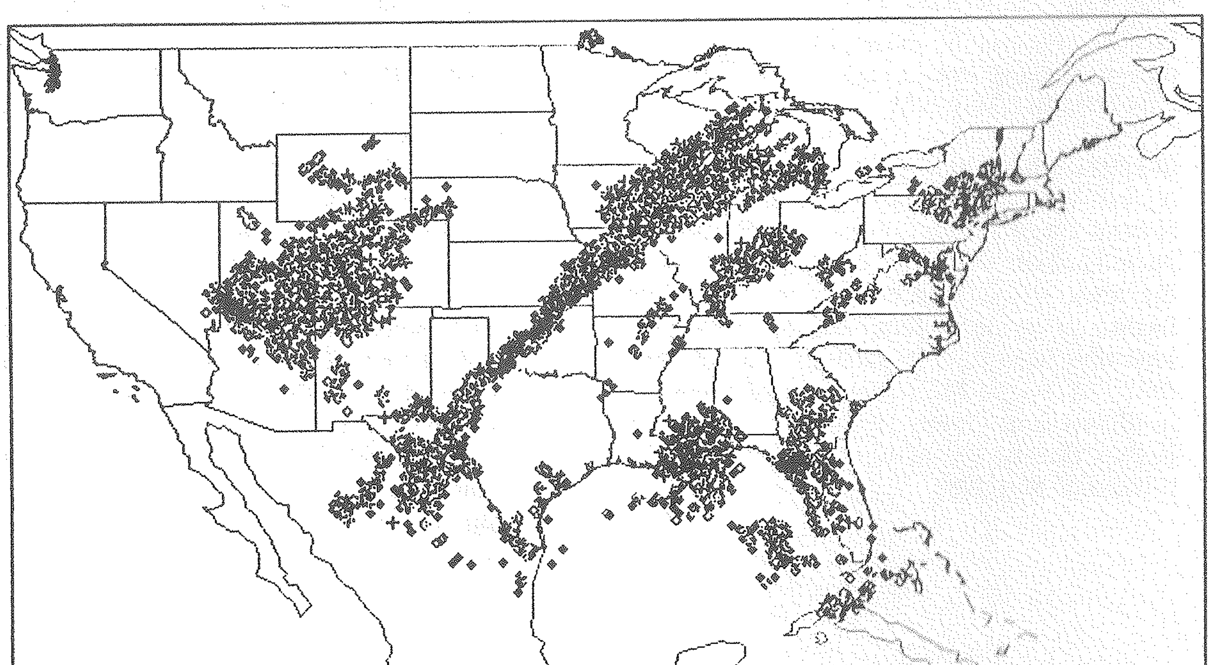

FIGURE 26. *Map of 44,975 flashes during less than 18 hours on a summer day over the continental United States and adjacent regions. Diamonds for negative flashes, plus signs for positive flashes.*

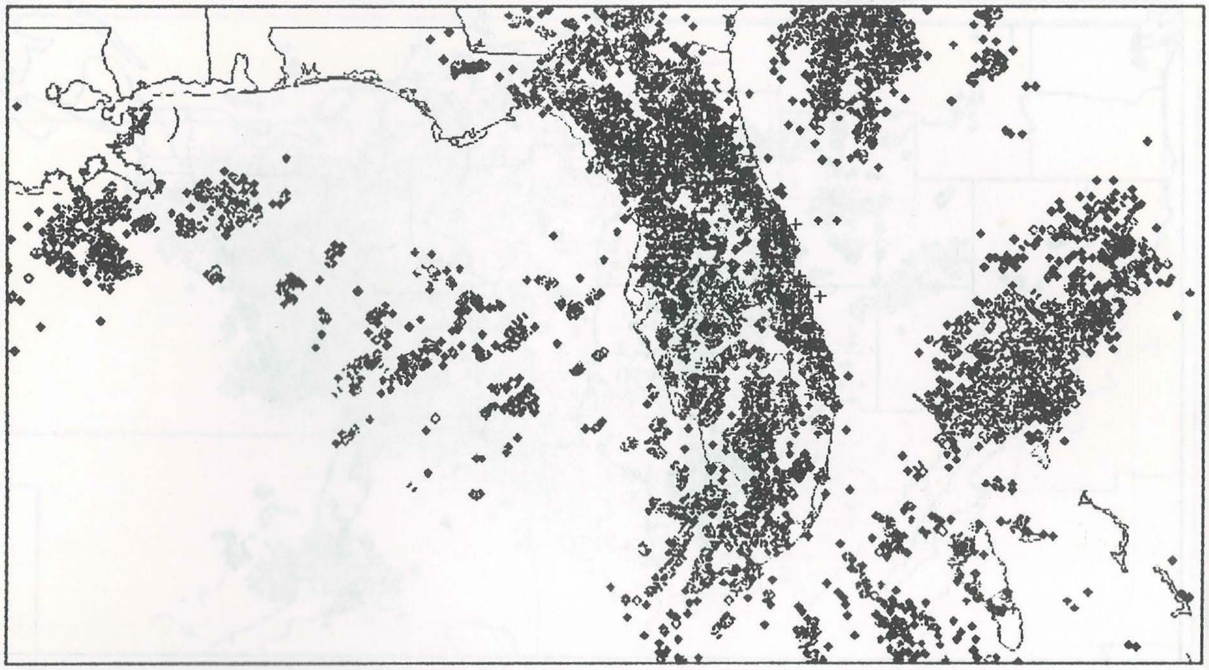

FIGURE 27. *Map of 26,838 flashes over central Florida for 24 hours showing sea breezes aligned along both coasts. Diamonds for negative flashes, plus signs for positive flashes.*

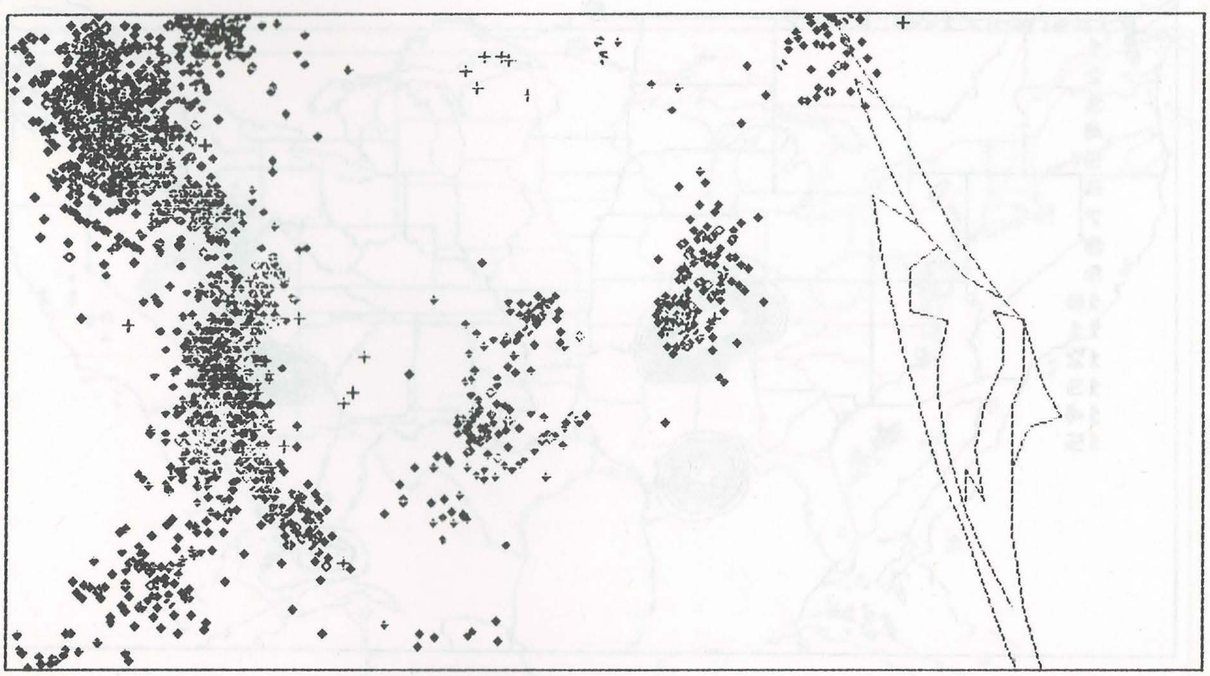

FIGURE 28. *Map of 2327 flashes over central Florida for 24 hours showing several separate storms. Diamonds for negative flashes, plus signs for positive flashes.*

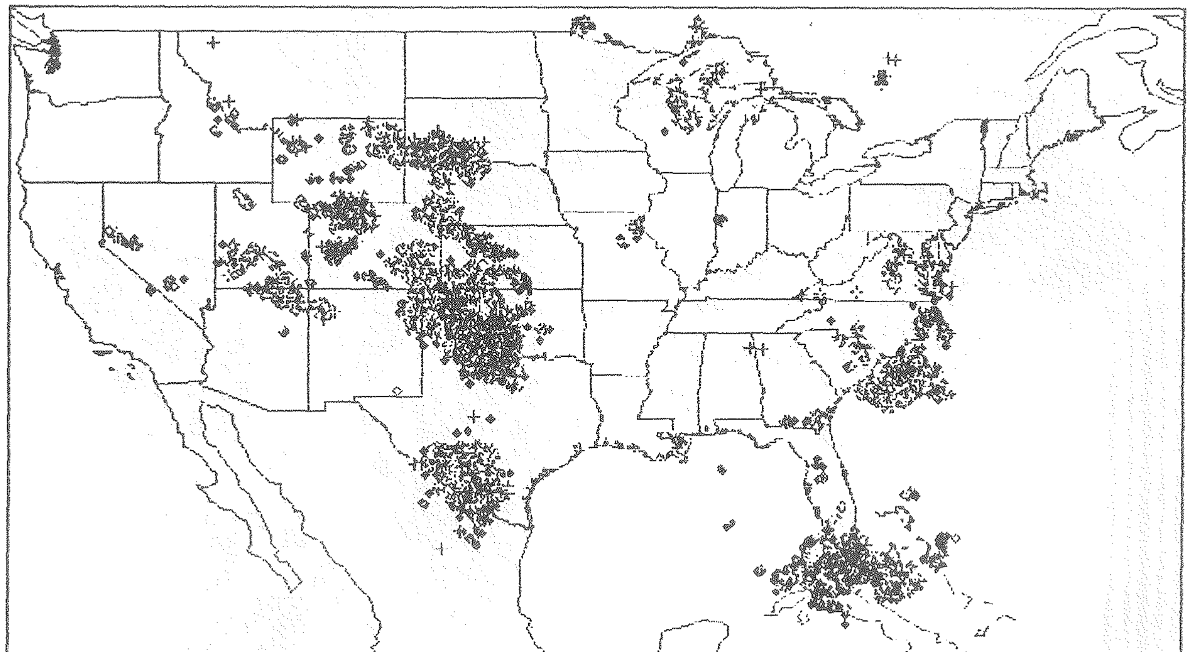

FIGURE 29. *Map of 44,991 CG flashes during less than 13 hours on a day with several large organized convective systems. Diamonds for negative flashes, plus signs for positive flashes.*

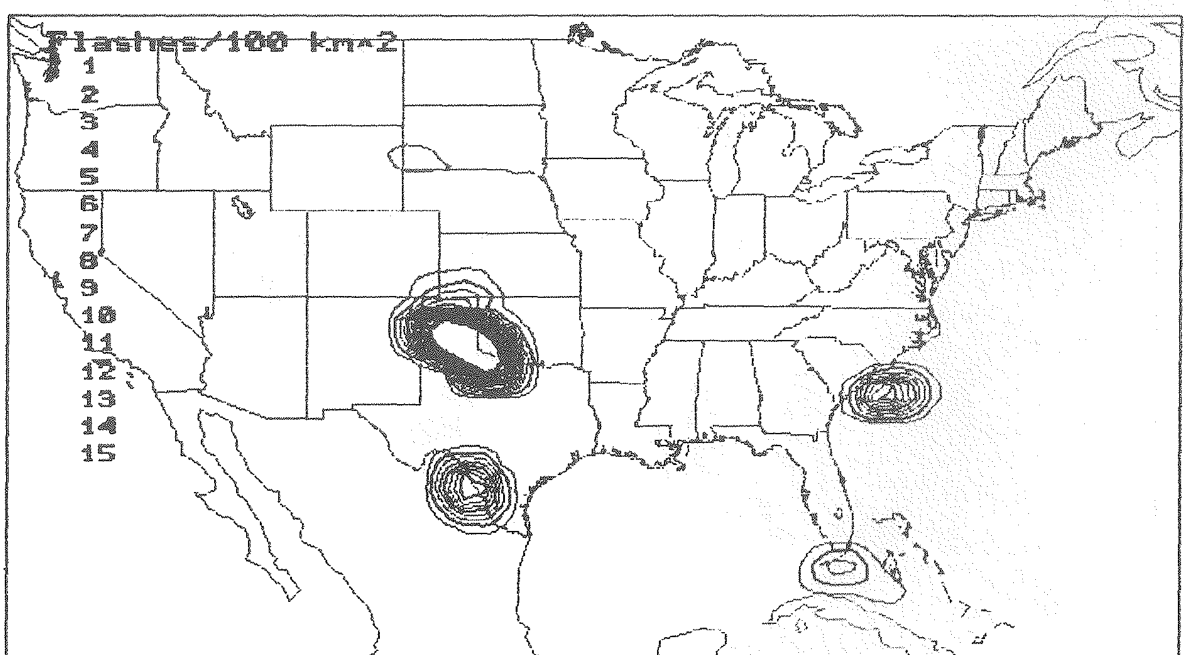

FIGURE 30. *Same time period and flashes as Figure 29, except contoured by flash density. Outer contours of all storms are 1 flash per 100 square km. Area inside smallest contour over Texas and Oklahoma exceeds 15 flashes per 100 square km.*

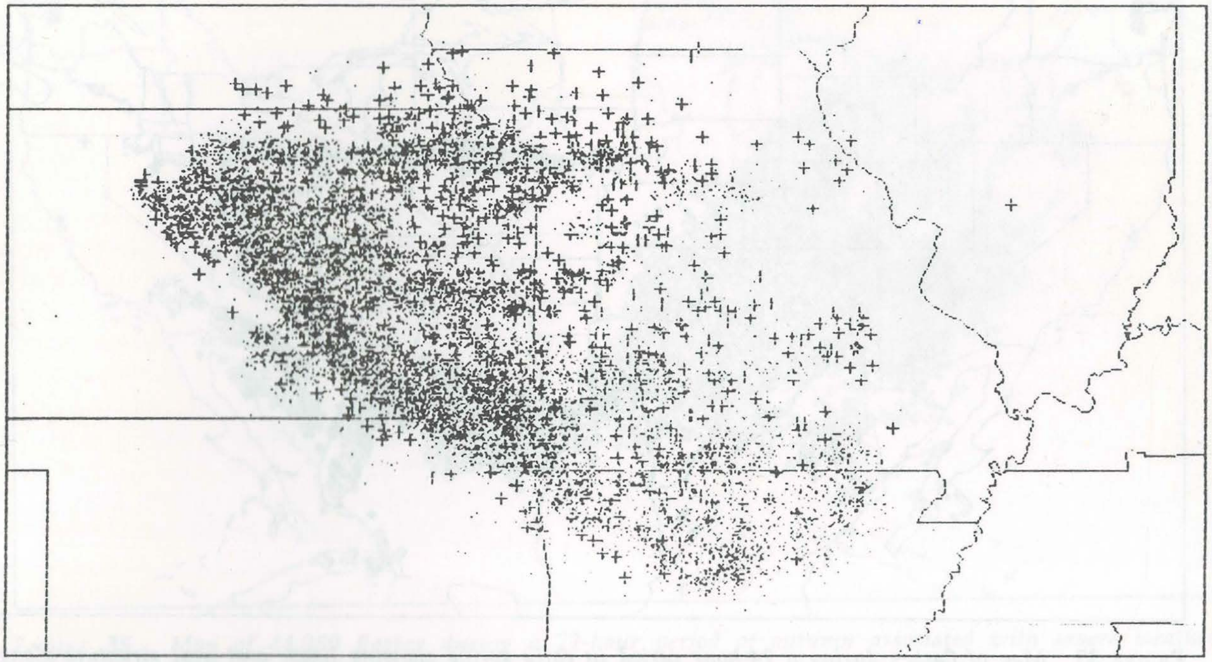

FIGURE 31. *Map of 20,186 CG flashes from a mesoscale convective system during 24 hours over the central U.S. Plains. Dots for negative flashes, plus signs for positive flashes.*

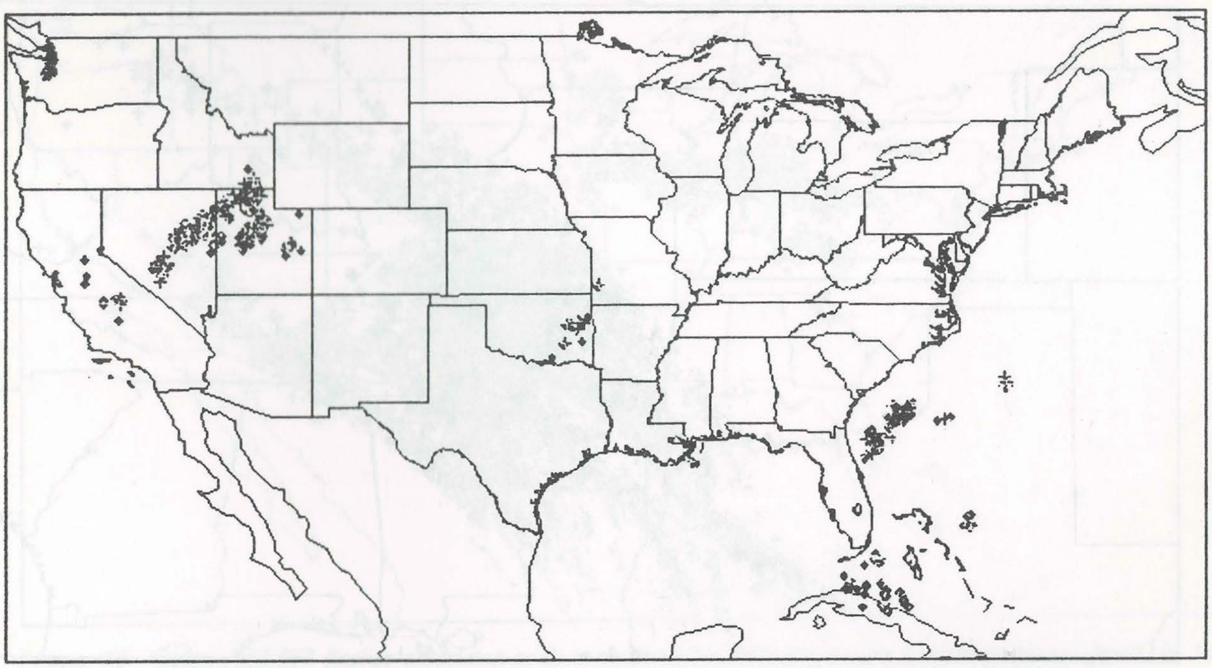

FIGURE 32. *Map of 868 flashes during a 24-hour period in late winter showing three thunderstorm areas associated with traveling disturbances. Diamonds for negative flashes, plus signs for positive flashes.*

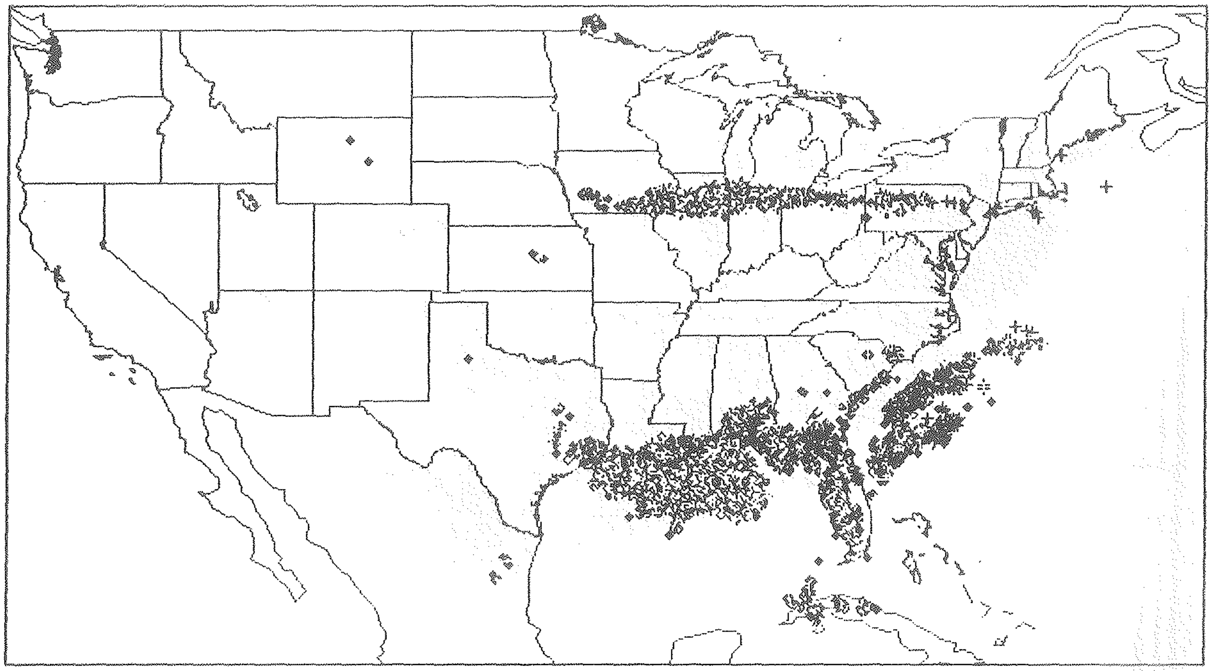

Figure 33. Map of flashes during a 24-hour period in early spring showing linear east-west structure along a warm front in the southern Great Lakes region. Diamonds for negative flashes, plus signs for positive flashes.

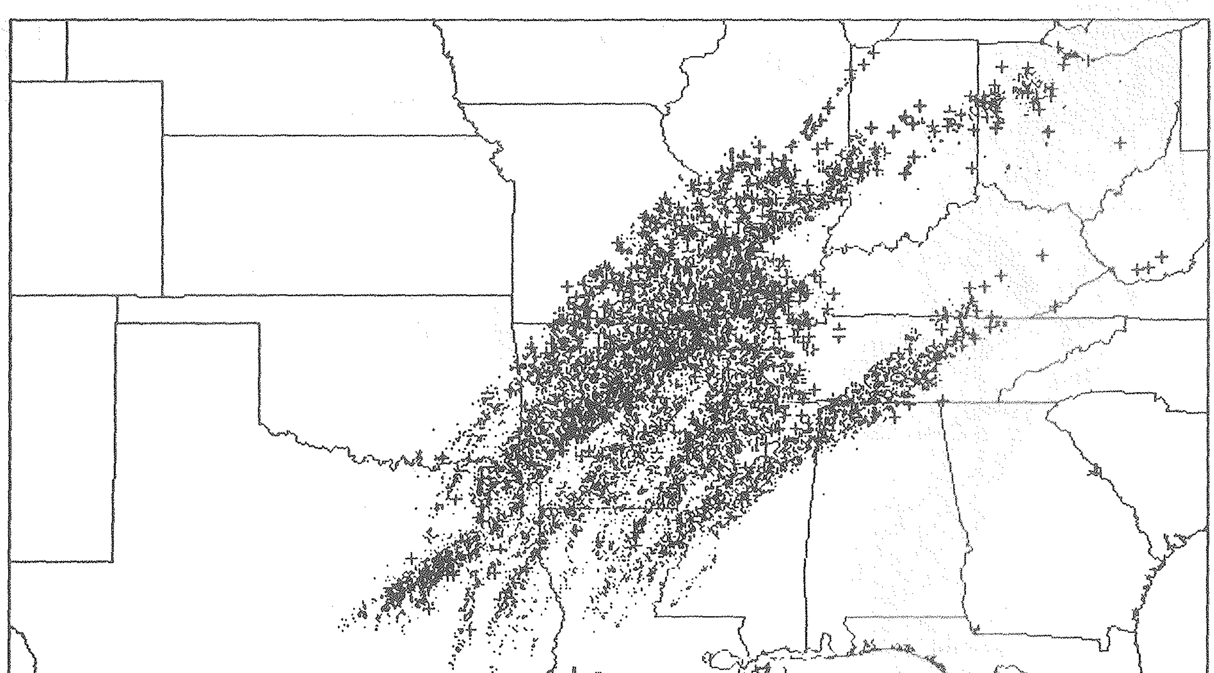

Figure 34. Map of 21,996 flashes during a 24-hour period in late autumn showing long linear structures in the convection over the central United States. Dots for negative flashes, plus signs for positive flashes.

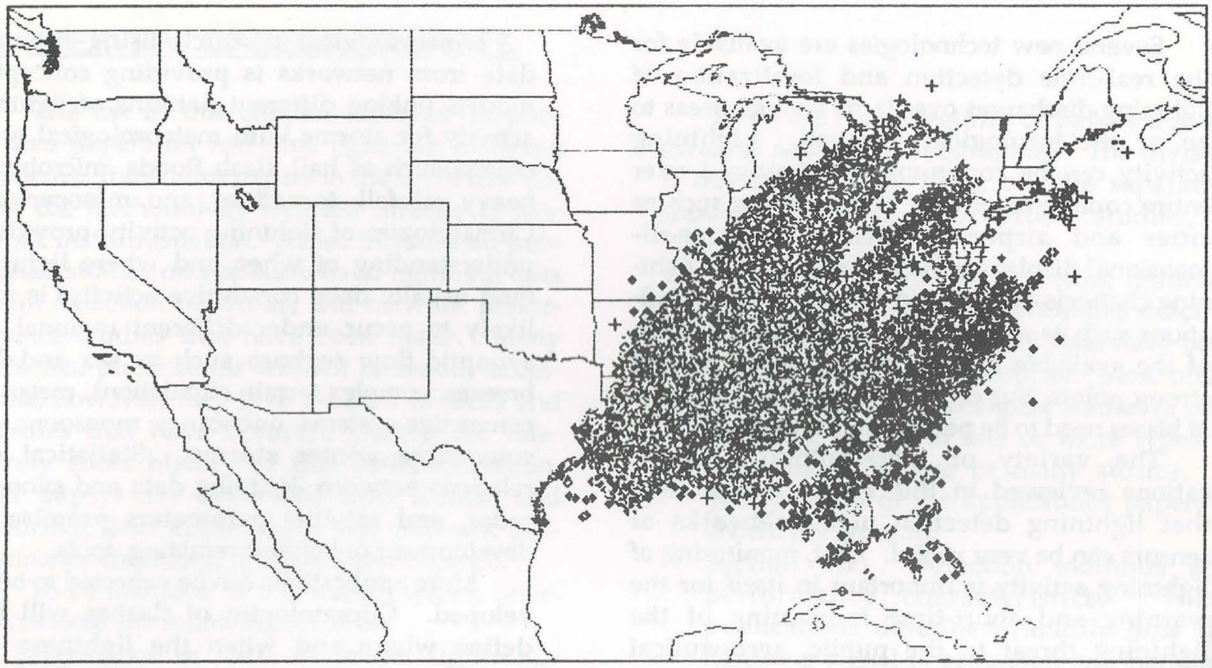

FIGURE 35. *Map of 44,080 flashes during a 22-hour period of autumn associated with severe weather. Diamonds for negative flashes, plus signs for positive flashes.*

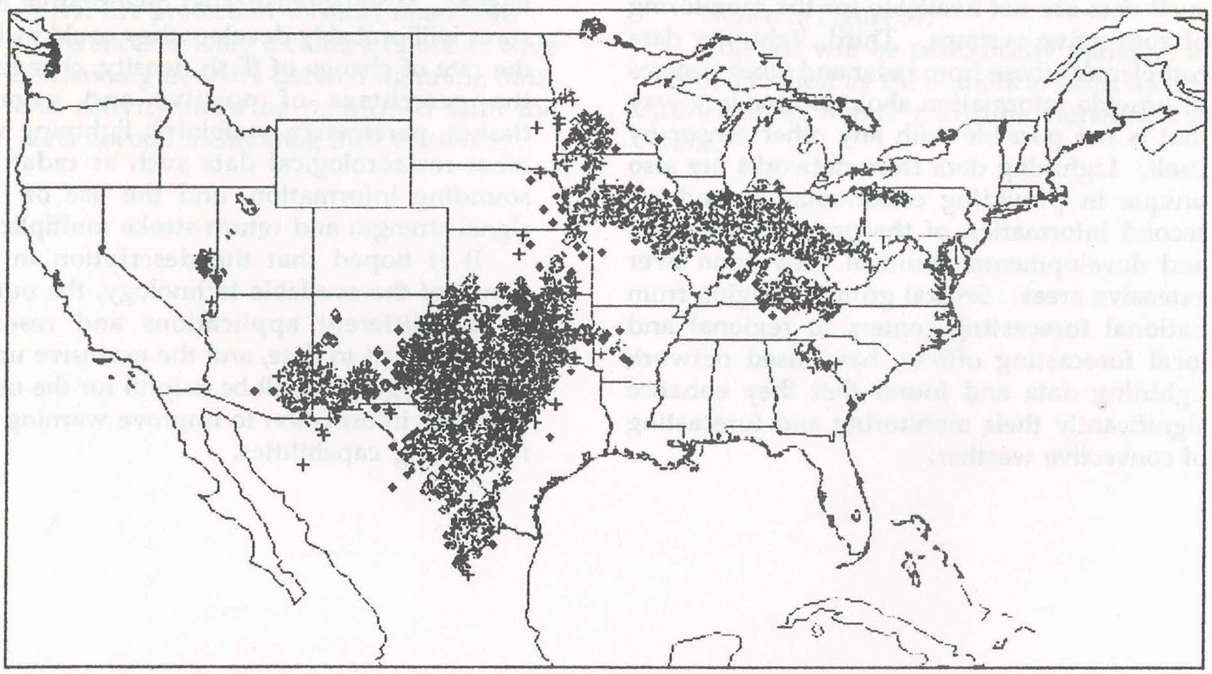

FIGURE 36. *Map of 19,517 flashes associated with a north-south cold front and east-west warm front in late winter. Diamonds for negative flashes, plus signs for positive flashes.*

4. CONCLUSIONS

Several new technologies are available for the real-time detection and localization of lightning discharges over large enough areas to be of meteorological interest. Lightning activity can be continuously monitored over entire continents or over smaller areas such as cities and airports. Real-time three-dimensional displays of both cloud and CG lightning channels can be used over sensitive installations such as airports and space centers. Each of the available systems have limitations and strong points, but calibrations and adjustments of biases need to be performed for them.

The variety of meteorological applications reviewed in this report makes clear that lightning detection using networks of sensors can be very useful. First, monitoring of lightning activity is important in itself for the warning and short-time forecasting of the lightning threat to the public, aeronautical operations, electric utilities, communications, forest and rangelands, and other interests. Second, lightning data can be used as a substitute for radar and satellite information if such data are not available for the monitoring of convective systems. Third, lightning data complement those from radar and other systems to provide information about storms in a way that is not possible with any other sensor by itself. Lightning data from networks are also unique in providing continuous, second-by-second information of the presence, location, and developmental trend of convection over extensive areas. Several groups, ranging from national forecasting centers to regional and local forecasting offices, have used network lightning data and found that they enhance significantly their monitoring and forecasting of convective weather.

Meteorological research using lightning data from networks is providing conceptual models linking different patterns of lightning activity for storms with meteorological phenomena such as hail, flash floods, microbursts, heavy rainfall, tornadoes, and mesocyclones. Climatologies of lightning activity provide an understanding of when and where lightning (and usually deep convective activity) is more likely to occur under different regional and synoptic flow regimes such as sea and lake breezes, complex terrain circulations, mesoscale convective systems, hurricanes, monsoons, and convective winter storms. Statistical correlations between lightning data and synoptic, radar, and satellite parameters promise the development of better forecasting tools.

More applications can be expected to be developed. Climatologies of flashes will help define where and when the lightning and thunderstorm threats are greatest. Real-time data uses will become more complex, and probably move far beyond the first level of use that concentrates on the location and density of flashes. More sophisticated quantitative measures will probably develop; they could include the rate of change of flash density, changes in the percentage of positive and negative flashes, parameters combining lightning with other meteorological data such as radar and sounding information, and the use of flash signal-strength and return-stroke multiplicity.

It is hoped that the description in this report of the available technology, the outline of the different applications and research accomplished to date, and the extensive up-to-date bibliography will be helpful for the use of lightning information to improve warning and forecasting capabilities.

5. BIBLIOGRAPHIES

A. OVERVIEW OF BIBLIOGRAPHIES

The list in this chapter includes all published papers on real-time lightning mapping systems. It includes papers in the 1970s describing the methodology that led directly to network instrumentation. It also includes all published studies on applications of lightning data from detection networks, and network performance studies that have been made. Many informal publications will not be readily accessible, however, they give the flow of ideas and studies that have occurred during the relatively short history of this instrumentation. All papers are separated into formal and informal, and applications and network performance emphases, in Table 3 and Figure 37.

To be included in the bibliographies, references need the following features:

- Networks of two or more lightning-detecting antennas
- Networks are generally used in a real-time operational setting by agencies providing weather information, services to utilities, forest fire protection, or other operations
- References usually include a figure or table containing network-derived lightning data
- An activity must be performed with the data beyond mentioning their existence.

There are two categories of papers that are given in separate bibliographies. The division is not always very clear, but the separation should help find appropriate studies, as follows:

- Section 5C. Applications using lightning network data. These publications describe how the lightning network data have been used for any type of purpose. Most often, they describe meteorological studies of how lightning relates to one or more types of other data, for one or many storms. A yearly graph of the applications papers is shown in Figure 38.
- Section 5D. Detection methods and performance characteristics. These publications describe primarily how the lightning signal is processed and handled, how detection networks collect and process their data, and feature the performance parameters of one or more networks. A yearly graph of the applications papers is shown in Figure 39.

This list will be periodically updated, and sent on request by the authors to assist access to information about real-time network flash data.

B. SUMMARY OF PUBLISHED PAPERS ON NETWORKS

TABLE 3. Number of published papers by year where the use or description of real-time lightning detection networks is included.

	Applications	Network performance	All
	Formal/Informal	Formal/Informal	Formal/Informal
1976	0/ 0	2/ 0	2/ 0
1977	0/ 1	0/ 0	0/ 1
1978	0/ 1	0/ 0	0/ 1
1979	0/ 1	2/ 0	2/ 1
1980	0/ 2	2/ 2	2/ 4
1981	0/ 1	0/ 0	0/ 1
1982	2/ 6	2/ 1	4/ 7
1983	1/13	0/ 3	1/16
1984	2/10	2/ 4	4/14
1985	0/16	1/ 3	1/19
1986	5/ 8	4/ 2	9/10
1987	8/ 9	5/ 1	13/10
1988	10/20	3/13	13/33
1989	7/33	9/10	16/43
1990	12/35	3/ 1	15/36
1991	12/18	3/12	15/30
1992	6/16	1/16	7/32
1993*	5/15	3/ 1	8/16
1994*	6/ 2	1/ 0	7/ 2
Total	76/207	43/69	119/276

*As of October 1993

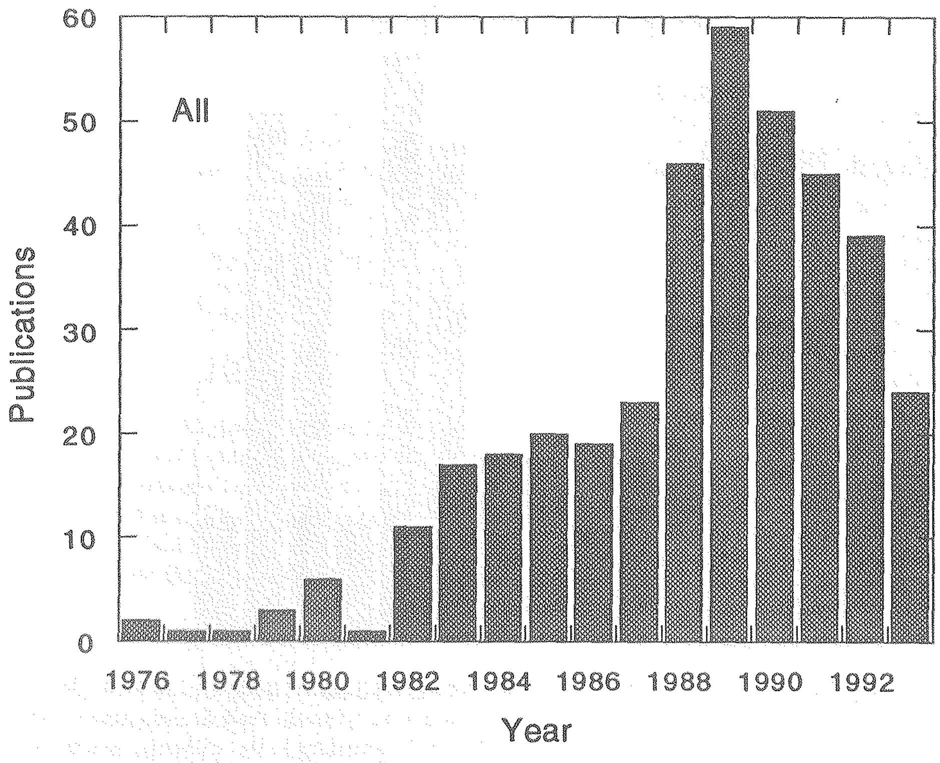

Figure 37. Total number of publications from Table 3 by year.

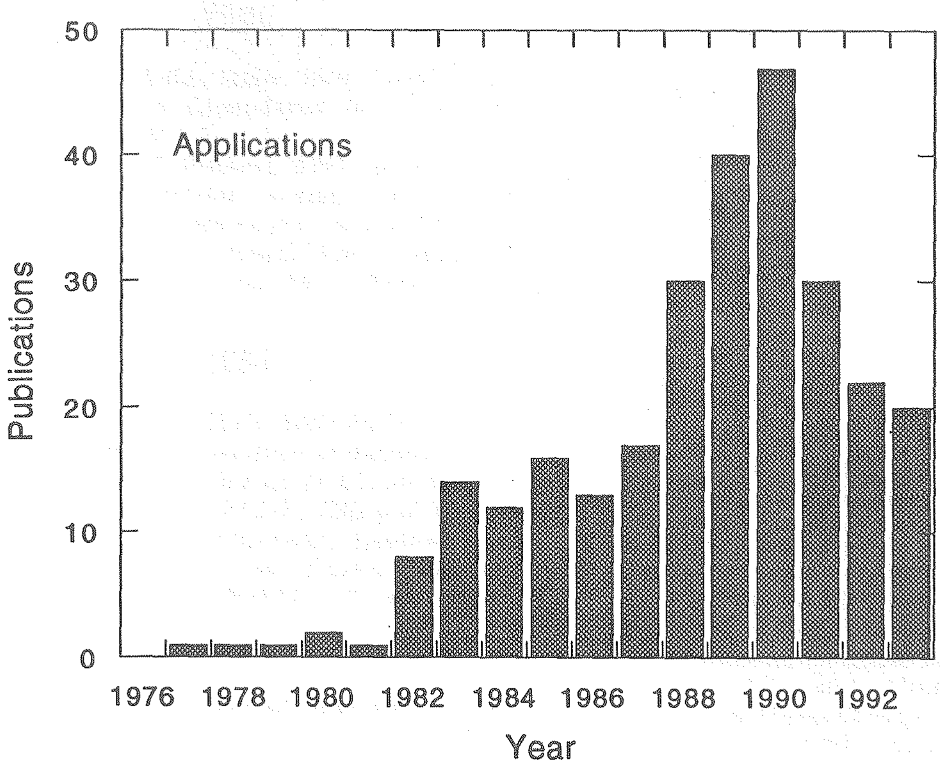

Figure 38. Publications describing applications in Table 3 by year.

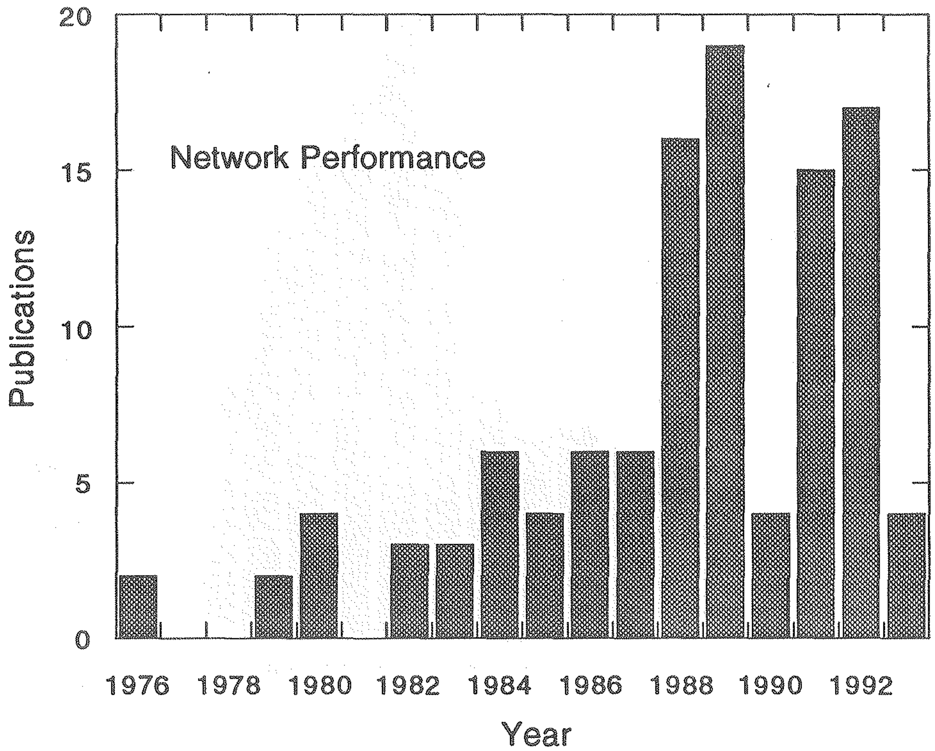

Figure 39. Publications describing network performance in Table 3 by year.

C. APPLICATIONS OF NETWORK LIGHTNING DATA

1977

Informal

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1978

Informal

Maier, M.W., A.G. Boulanger, and J. Sarlat, 1978: Cloud-to-ground lightning frequency over south Florida. Preprints, Conference on Cloud Physics and Atmospheric Electricity, July 31-August 4, Issaquah, Washington, American Meteorological Society, Boston, 605-610.

1979

Informal

Maier, M.W., A.G. Boulanger, and R.I. Sax, 1979: An initial assessment of flash density and peak current characteristics of lightning flashes to ground in south Florida. U.S. Nuclear Regulatory Commission Report NUREG/CR-1024, 43 pp.

1980

Informal

Maier, M.W., and R.L. Holle, 1980: Cloud-ground lightning rate dependence on radar echo height. *EOS*, **61**, 975.

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1983

Formal

Orville, R.E., R.W. Henderson, and L.F. Bosart, 1983a: An east coast lightning detection network. *Bulletin of the American Meteorological Society*, **64**, 1029-1037.

Informal

Geotis, S.G., and R.E. Orville, 1983: Simultaneous observations of lightning ground strokes and radar reflectivity patterns. Preprints, 21st Conference on Radar Meteorology, September 19-23, Edmonton, Alberta, Canada, American Meteorological Society, Boston, 57-58.

Goodman, S.J., 1983: Lightning activity associated with severe storms embedded within a mesoscale convective storm complex. Preprints, 13th Conference on Severe Local

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6. ACRONYMS AND DEFINITIONS

ARSI	Atmospheric Research Systems Incorporated.
CG	Cloud-to-ground flash (ground flash, ground strike).
GDS	GeoMet Data Systems, Incorporated.
LLP	Lightning Location and Protection, Incorporated.
LPATS	Lightning Position and Tracking System.
Mapping system	A system that maps lightning flashes by locating sources of electromagnetic radiation.
ONERA	Office National d'Etudes et de Recherches Aérospatiales.
Polarity	
Negative	CG flash lowering negative charge to ground (most common).
Positive	CG flash lowering positive charge to ground (less common).
SAFIR	Systeme d'Alerte Foudre par Interferometrie Radioelectrique.
TOA	Time-of-arrival method of lightning detection.
Total lightning	All negative and positive CG and cloud flashes.

NATIONAL SEVERE STORMS LABORATORY

The NSSL Technical Memoranda, beginning at No. 28, continue the sequence established by the U.S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151, a microfiche version for $4.00 or a hard copy, cost depending upon the number of pages. NTIS numbers are given below in parenthesis.

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*U.S. GOVERNMENT PRINTING OFFICE:1993-573-013/89054